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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.

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-

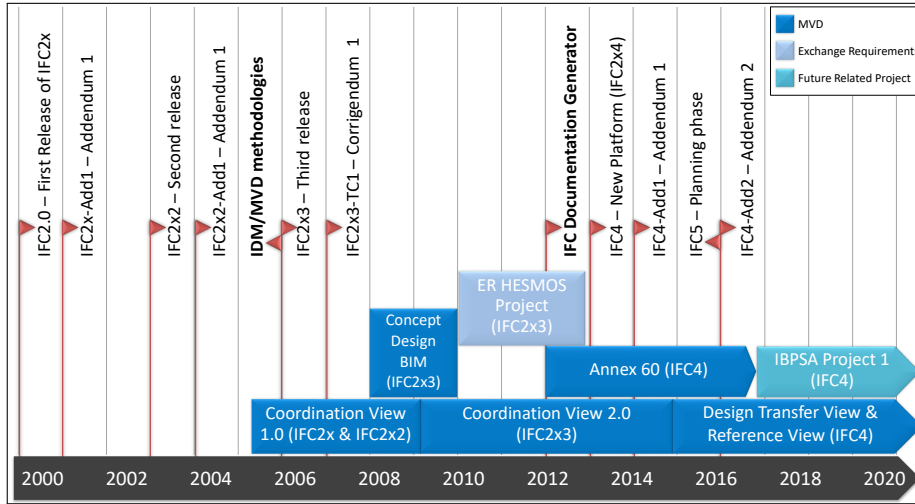


Figure 1: Summary of the IFC releases with key enabling technologies for IFC implementation together with MVD development over the years.

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

130 2.1. Review of Energy Related MVDs

131 Since the introduction of the MVD concept, organisations started develop-
 132 ing their own MVDs to support internal processes based on the IFC schema
 133 (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. 2nd 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 2nd 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 1st level space boundaries only. Consequently
153 and for the purposes of BEPS, an additional process that added 2nd level space
154 boundaries using a conversion tool was required [30]. With the 1st 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 resources	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.

165 3. Information Exchange Process to Support BEPS

166 The IEA EBC Annex 60 project promotes research and development of new
167 methods to help design and operate energy efficient buildings and communities
168 [21]. Activity 1.3 of the Annex 60 focuses on the complex issue of transforming
169 a digital model of a building and its HVAC systems into semi-automatically
170 generated Modelica code that can be readily used for advanced BEPS models.
171 The main objective of this activity is to address the prevailing tedious, cumber-
172 some and error-prone process of manual data conversion and model generation
173 by providing a semi-automatic method of data transformation.

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

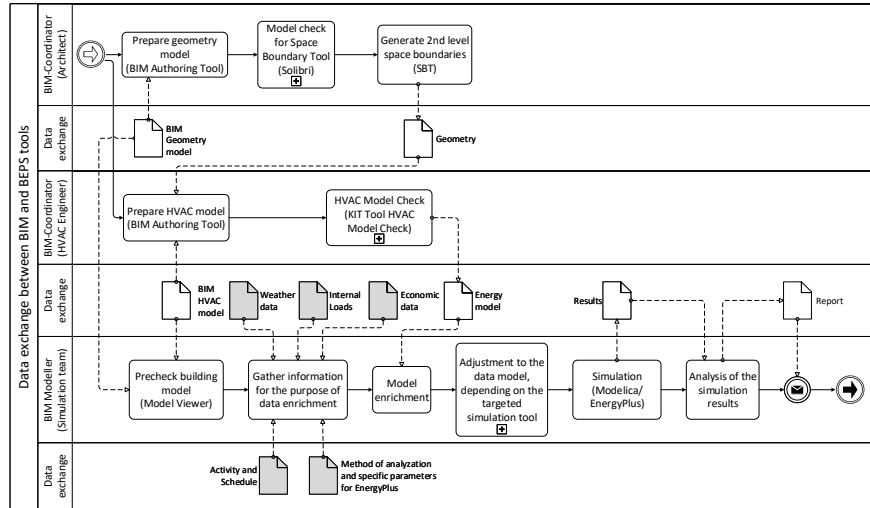


Figure 3: Process map for the exchange of information between BIM and BEPS engines, Modelica and/or EnergyPlus.

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

194 Based on the geometry model of the building created by the architect, the
 195 HVAC engineer adds information about HVAC systems. At this point, the
 196 engineer uses static/conservative dimension methods to specify systems com-
 197 ponents and parameters. Quality assurance is an important precondition for a
 198 qualified simulation process. Thus, it is necessary to have a coherency check
 199 of the IFC file to ensure that modelling requirements are satisfied. Based on
 200 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 simu-
227 lation 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).

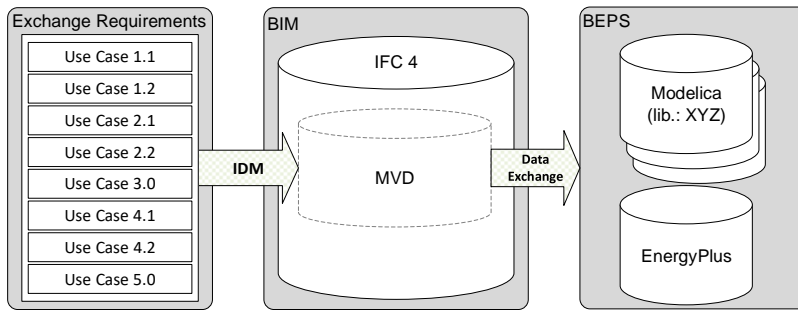


Figure 4: Methodology diagram for definition of the MVD using a collection of use cases to extract the information needed by BEPS tools.

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-

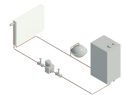
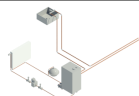

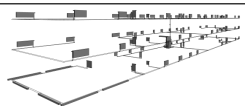
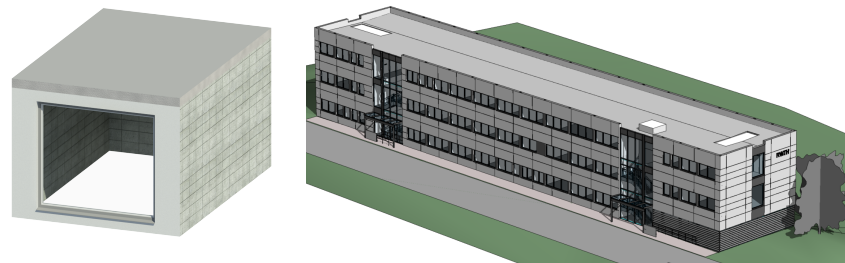
<i>Identifier and Name</i>	<i>HVAC System (generation + emission)</i>	<i>Revit Model</i>
1.1 Boiler	Gas boiler and radiator	
1.2 Boiler	Gas boiler, buffer storage for domestic hot water and radiator	
2.1 Heat Pump	Heat pump, buffer storage and radiator	Missing IFC entity to represent the heat pump
2.2 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.



(a) Single Room

(b) Multi-Zone

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 (kg/m^3), thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$) 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

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

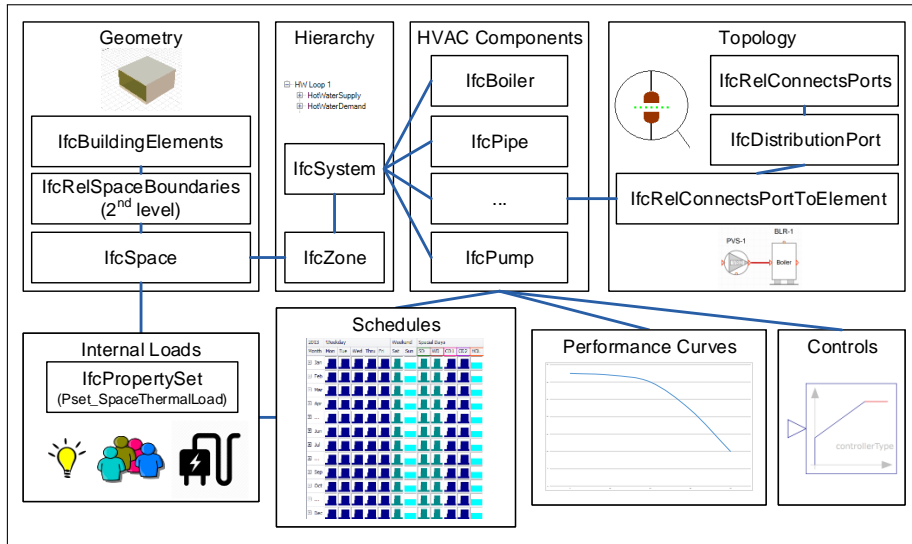


Figure 7: High level overview for the Building Energy Performance Simulation MVD.

283 The accuracy of a BEPS model depends significantly on the correct rep-
 284 resentation of building *Geometry*. As a result, geometrical definitions should
 285 include material data such as thermal properties and thicknesses; construction
 286 layers and all types of 2^{nd} level space boundaries which link spaces to building
 287 components.

288 *Internal Loads* are any sensible and latent heat emitted within a space from
 289 any source. The most common sources are: occupants, lighting and equip-
 290 ment. IFC4 already has designated properties for internal loads such as: max-
 291 imal/minimum temperature of the space; maximum number of people; total
 292 sensible heat or energy gained; lighting loads and percent of sensible load to ra-
 293 diant heat. However, the dynamic temporal nature of schedules is still missing
 294 and this is a crucial requirement for BEPS.

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

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

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

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

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

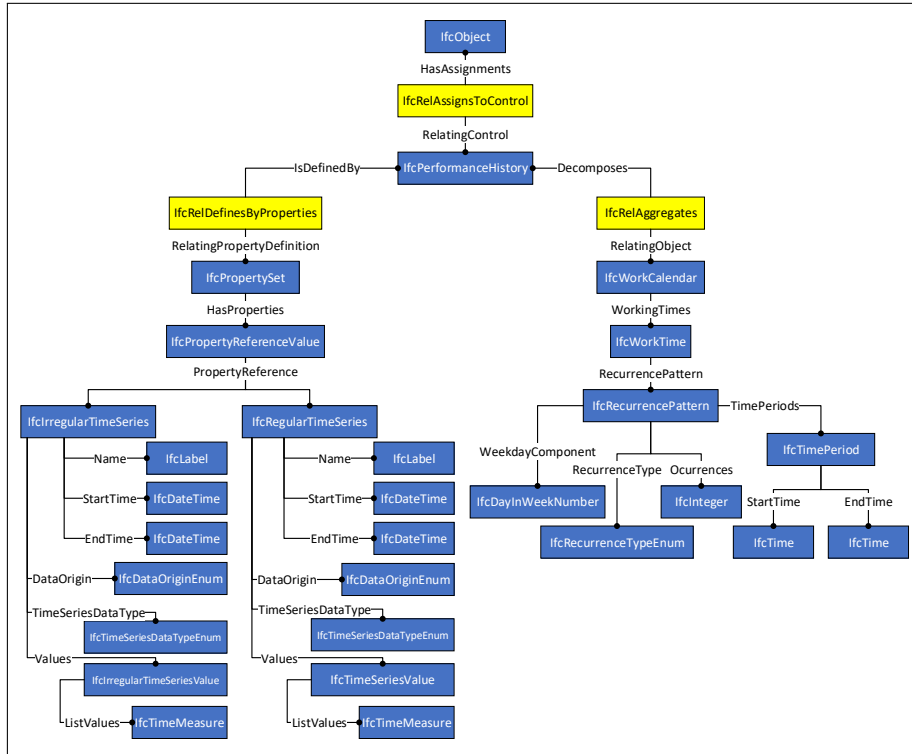


Figure 8: Structure of the MVD concept developed for representing schedules definition on energy simulation.

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,

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

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

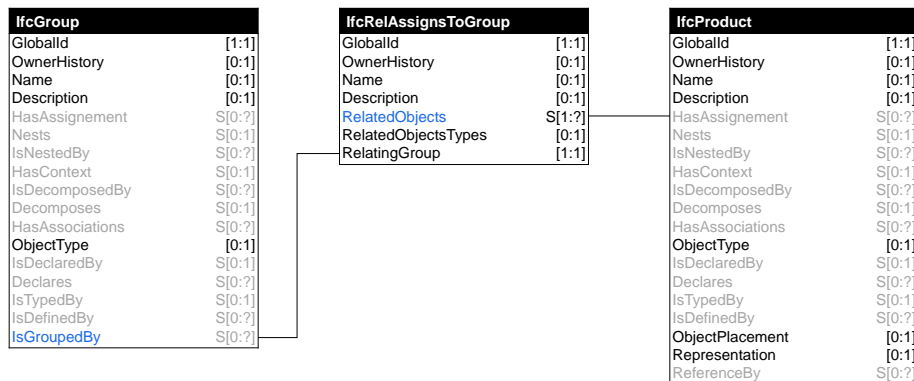


Figure 9: Instance diagram of the Group Assignment Concept used to group HVAC systems. The pipe and the cable segments are not represented.

354 Several enhancements to *HVAC components* were made in the IFC4 schema.
 355 In particular, component definitions became more detailed. For example, an
 356 '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 (CO₂) and medium (ReturnWater).

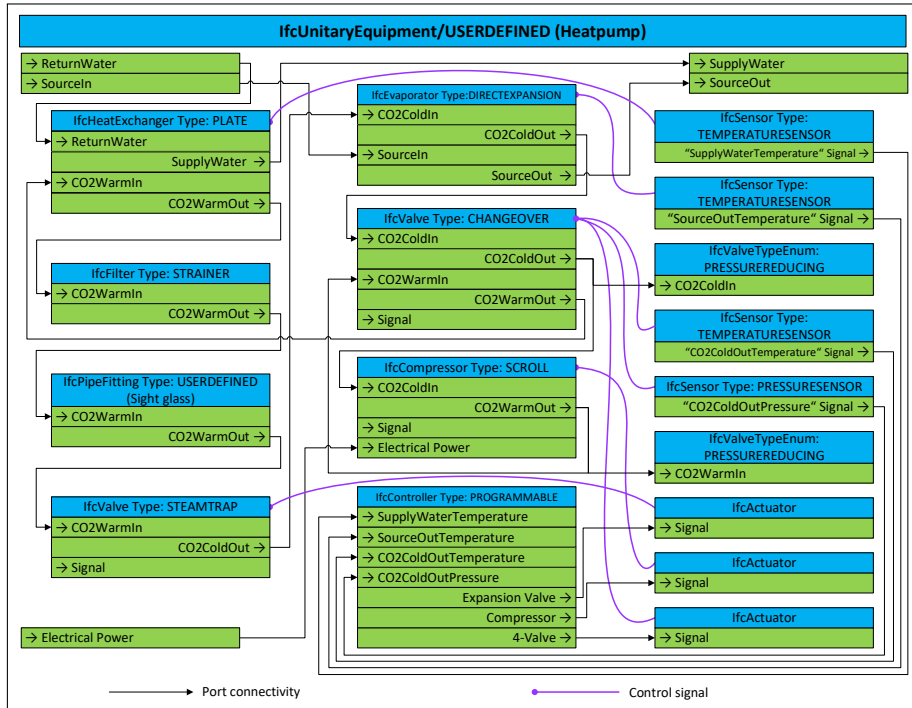


Figure 10: Concept to define a Heatpump entity, using the methodology provided by IfcUnitaryEquipment [42].

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

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

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

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

389 Overall 49 additional properties were defined and added to existing objects
390 to support the data exchange between BIM and BEPS tools (Figure 11). The
391 missing properties were identified by analysing how the HVAC components are
392 modelled in EnergyPlus version 8.2 and two Modelica libraries (AixLib from
393 Aachen and BuildingSystems from UdK Berlin), and comparing the objects to
394 the existing IFC4 properties set definition for the corresponding object. The
395 missing properties were introduced to overcome the lack of information needed
396 for BEPS. Such processes require a comprehensive analysis of the given entities,
397 property sets and data types of the IFC4 data model. Additional properties were
398 developed for eight different HVAC components (IfcBoiler, IfcCoil, IfcDuctSeg-
399 ment, IfcFan, IfcPump, IfcSpaceHeater, IfcController, IfcValve), as well as, for
400 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
	OverallHeatTransCoeffUFactorFromAirToAir		MaxWaterFlowRate
PSim_Window	OverallMoistTransCoeffFromAirToAir	PSim_Material	RadiantFraction
	TransmissionCoefficient		CoefficientOfHeatTransfer
	TransmissionCoefficientShading		Emissivity
PSim_Space	RadiantEnergyFluenceRateShading	PSim_ControllerPID	AbsorptionCoefficient
	NumberOfPeopleWithMachines		Setpoint
	RatioConvectiveHeatMachines		IntegrativeTimeConstant
	RatioConvectiveHeatPeople		DerivativeTimeConstant
	RatioConvectiveHeatLights		LimitOfPIDOutput
	MaxUserACH		WeightP
	MaxOverheatingACH		WeightD
	MaxSummerACH		ControllerVariable
WinterReductionACH	ControllerType		
PSim_Boiler	DesignWaterFlowRate	PSim_Pump	FractionOfMotorInefficienciesToFluidStream
	ParasiticElectricLoad		ControlType
	NominalMassFlowRate		SkinLossRadiativeFraction
	PLREfficiency		HeadMax
Qsim_BuildingQuantities	LenghtLongerSide	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	<p>Boiler Efficiency Curve</p> $= C1 + C2(PLR) + C3(PLR)^2 + C4(Twater) + C5(Twater)^2 + C6(PLR)(Twater) + C7(PLR)^3 + C8(Twater)^3 + C9(PLR)^2(Twater) + C10(PLR)(Twater)^2$ <ul style="list-style-type: none"> • PLR = Part Load Ratio • Twater = Inlet Water Temperature • The values are stored in a Set of <i>IfcPropertySingleValue</i> using <i>HasProperties</i> in the following order: C1 ... C10. • The boundary conditions for the performance curve are stored in the same Set after the coefficients in the following order: <i>MinimumX, MaximumX, MinimumY, MaximumY, MinimumOutput, MaximumOutput</i> 	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.

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

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

435 usability and other subjects.

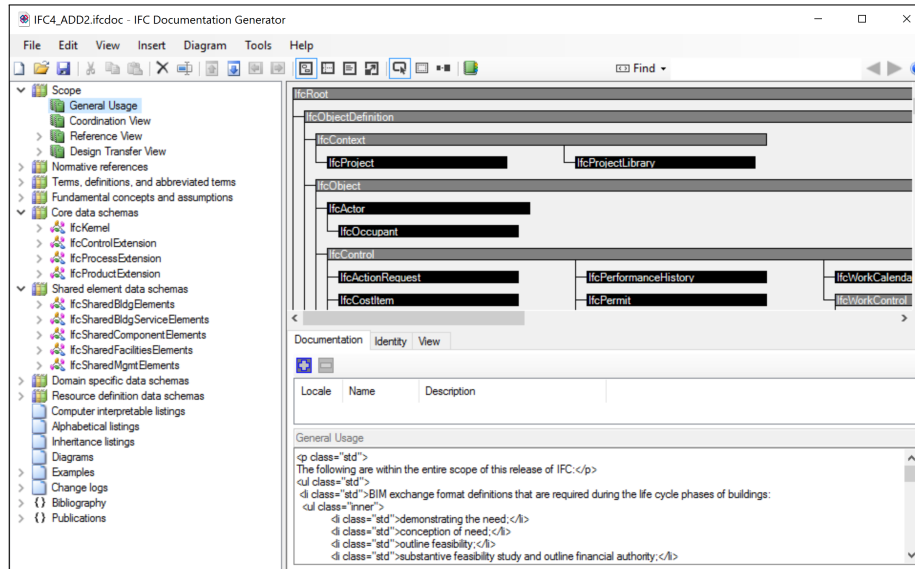


Figure 13: The user interface of IfcDoc tool loaded with baseline file.

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.

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

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

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

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

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

520 One of the limitations encountered during the development of the MVD is
521 that most BIM applications do not provide in house IFC4 export capabilities.
522 For instance, Revit provides an add-on to overcome this issue but still lacks a
523 flawless IFC4 file generation according to the ISO 16739. Additionally, we have
524 found that for Revit System Families (such as pipe segment, pipe fitting, duct
525 segment, etc.) we could not assign property sets to IFC types. The only way to
526 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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587 **References**

- 588 [1] A. Aksamija, BIM-Based Building Performance Analysis: Evaluation and
589 Simulation of Design Decisions, in: 2012 ACEEE Summer Study on Energy
590 Efficiency in Buildings, 2012, p. 12.
591 URL [http://www.aceee.org/files/proceedings/2012/data/papers/
592 0193-000367.pdf](http://www.aceee.org/files/proceedings/2012/data/papers/0193-000367.pdf)
- 593 [2] R. J. Hitchcock, Improving building life-cycle information management
594 through documentation and communication of projects objectives, in: CIB
595 Proceedings, 1995, p. 10.
596 URL <https://eetd.lbl.gov/node/52092>
- 597 [3] M. Martínez-Rojas, N. Marín, M. A. Vila, The Role of Information
598 Technologies to Address Data Handling in Construction Project Manage-
599 ment, *Journal of Computing in Civil Engineering* 30 (4) (2016) 04015064.
600 doi:10.1061/(ASCE)CP.1943-5487.0000538.
- 601 [4] V. Bazjanac, IFC BIM-based Methodology for Semi-Automated Building
602 Energy Performance Simulation, in: 25th CIB_W78, Santiago, Chile, 2008,
603 p. 15.
604 URL <http://escholarship.org/uc/item/0m8238pj>
- 605 [5] M. Wetter, M. Bonvini, T. S. Noudui, Equation-based languages A new
606 paradigm for building energy modeling, simulation and optimization, *En-
607 ergy and Buildings* 117 (2016) 290–300. doi:10.1016/j.enbuild.2015.
608 10.017.
- 609 [6] V. Bazjanac, Acquisition of Building Geometry in the Simulation of Energy
610 Performance, in: 7th IBPSA, Rio de Janeiro, Brasil, 2001, pp. 305–311.
611 URL [http://www.inive.org/members_area/medias/pdf/inive/ibpsa/
612 ufsc438.pdf](http://www.inive.org/members_area/medias/pdf/inive/ibpsa/ufsc438.pdf)
- 613 [7] P. Berkeley, P. Haves, E. Kolderup, Impact of Modeler Decisions on Simu-

- 614 lation Results, in: ASHRAE/IBPSA-USA Building Simulation Conference,
615 Atlanta, GA, 2014, pp. 2923–2930.
- 616 [8] A. Cormier, S. Robert, P. Roger, L. Stephan, E. Wurtz, Towards a BIM-
617 Based Service Oriented Platform: Application to Building Energy Perfor-
618 mance Simulation, in: 12th IBPSA Conference, Sydney, Australia, 2011,
619 pp. 2309–2316.
620 URL http://www.ibpsa.org/proceedings/BS2011/P_1728.pdf
- 621 [9] K. Hiyama, S. Kato, M. Kubota, J. Zhang, A new method for reusing
622 building information models of past projects to optimize the default con-
623 figuration for performance simulations, *Energy and Buildings* 73 (2014)
624 83–91. doi:10.1016/j.enbuild.2014.01.025.
- 625 [10] W. Jeong, J. B. Kim, M. J. Clayton, J. S. Haberl, W. Yan, A framework
626 to integrate object-oriented physical modelling with building information
627 modelling for building thermal simulation, *Journal of Building Performance*
628 *Simulation* 9 (1) (2016) 50–69. doi:10.1080/19401493.2014.993709.
629 URL [http://www.tandfonline.com/doi/full/10.1080/19401493.](http://www.tandfonline.com/doi/full/10.1080/19401493.2014.993709)
630 [2014.993709](http://www.tandfonline.com/doi/full/10.1080/19401493.2014.993709)
- 631 [11] J. Choi, J. Shin, M. Kim, I. Kim, Development of openBIM-based energy
632 analysis software to improve the interoperability of energy performance
633 assessment, *Automation in Construction* 72 (2016) 52–64. doi:10.1016/
634 [j.autcon.2016.07.004](http://www.tandfonline.com/doi/full/10.1016/j.autcon.2016.07.004).
- 635 [12] B. Dong, K. P. Lam, Y. C. Huang, G. M. Dobbs, A comparative study
636 of the IFC and gbXML informational infrastructures for data exchange in
637 computational design support environments, in: *Building Simulation 2007*,
638 2007, pp. 1530–1537.
- 639 [13] V. Bazjanac, T. Maile, C. Nytsch-Geusen, GENERATION OF BUILDING
640 GEOMETRY FOR ENERGY PERFORMANCE SIMULATION USING
641 MODELICA, in: *BauSim Conference*, Dresden, Germany, 2016, pp. 361–
642 368.

- 643 [14] EN ISO, EN ISO 16739:2016 - Industry Foundation Classes (IFC) for
644 data sharing in the construction and facility management industries (ISO
645 16739:2013) (2016).
646 URL [http://www.din.de/en/getting-involved/
647 standards-committees/nabau/projects/wdc-proj:din21:250357268](http://www.din.de/en/getting-involved/standards-committees/nabau/projects/wdc-proj:din21:250357268)
- 648 [15] G. I. Giannakis, G. N. Lilis, M. A. Garcia, G. D. Kontes, C. Valmaseda,
649 D. V. Rovas, A Methodology to Automatically Generate Geometry Inputs
650 for Energy Performance Simulation From IFC BIM Models, in: Building
651 Simulation Conference 2015, Hyderabad, India, 2015, pp. 504–511.
- 652 [16] BuildingSMART, MVD Overview summary (2016).
653 URL [http://www.buildingsmart-tech.org/specifications/
654 mvd-overview/mvd-overview-summary](http://www.buildingsmart-tech.org/specifications/mvd-overview/mvd-overview-summary)
- 655 [17] R. Wimmer, T. Maile, J. O’Donnell, J. Cao, C. van Treeck, Data-
656 requirements specification to support BIM-based HVAC-definitions in Mod-
657 elica, in: BauSIM 2014, Aachen, Germany, September, 2014, 2014, pp.
658 99–107.
- 659 [18] R. Wimmer, J. Cao, P. Remmen, T. Maile, J. O’Donnell, J. Frisch, R. Stre-
660 blow, D. Müller, C. van Treeck, Implementation of advanced BIM-based
661 mapping rules for automated conversion to Modelica, in: Proceedings of
662 the 14th IBPSA Conference, 2015, pp. 419–426.
- 663 [19] M. Thorade, J. Rädler, P. Remmen, T. Maile, R. Wimmer, J. Cao,
664 M. Lauster, C. Nytsch-Geusen, D. Müller, C. van Treeck, An open
665 toolchain for generating Modelica code from Building Information Mod-
666 els, in: P. Fritzson, H. Elmqvist (Eds.), 11th International Modelica Con-
667 ference, Modelica Association, Paris, France, 2015, pp. 383–391. doi:
668 10.3384/ecp15118383.
- 669 [20] R. Wimmer, S. Pinheiro, J. O’Donnell, S. Muhic, T. Maile, V. Bazjanac,
670 J. Frisch, C. van Treeck, Realizing openBIM - Development of a BIM Model

- 671 View Definition for Advanced Building Energy Performance Simulation, GI
672 - Gebäudetechnik in Wissenschaft & Praxis 04 (2017) 276–294.
- 673 [21] M. Wetter, C. van Treeck, New Generation Computational Tools for Build-
674 ing & Community Energy Systems - Annex 60 Final Report, Tech. rep.,
675 International Energy Agency (2017).
676 URL <http://www.iea-annex60.org/>
- 677 [22] M. Laakso, A. Kiviniemi, The IFC standard - A review of history, develop-
678 ment, and standardization, Journal of Information Technology in Construc-
679 tion (ITcon) 17 (2012) 134–161.
680 URL [http://www.itcon.org/data/works/att/2012_9.content.01913.](http://www.itcon.org/data/works/att/2012_9.content.01913.pdf)
681 pdf
- 682 [23] BuildingSMART, Coordination View Version 2.0 Summary Welcome to
683 buildingSMART-Tech.org (2016).
684 URL [http://www.buildingsmart-tech.org/specifications/](http://www.buildingsmart-tech.org/specifications/ifc-view-definition/coordination-view-v2.0/summary)
685 [ifc-view-definition/coordination-view-v2.0/summary](http://www.buildingsmart-tech.org/specifications/ifc-view-definition/coordination-view-v2.0/summary)
- 686 [24] T. Liebich, IFC4 - The New buildingSMART Standard: What's new in
687 IFC4?, Tech. rep., buildingSMART International (2013).
688 URL [http://www.buildingsmart-tech.org/specifications/](http://www.buildingsmart-tech.org/specifications/ifc-releases/ifc4-release/buildingSMART_IFC4_WhatisNew.pdf)
689 [ifc-releases/ifc4-release/buildingSMART_IFC4_WhatisNew.pdf](http://www.buildingsmart-tech.org/specifications/ifc-releases/ifc4-release/buildingSMART_IFC4_WhatisNew.pdf)
- 690 [25] BuildingSMART, IFC4 Reference View Welcome to buildingSMART-
691 Tech.org (2016).
692 URL [http://www.buildingsmart-tech.org/specifications/](http://www.buildingsmart-tech.org/specifications/ifc-view-definition/ifc4-reference-view)
693 [ifc-view-definition/ifc4-reference-view](http://www.buildingsmart-tech.org/specifications/ifc-view-definition/ifc4-reference-view)
- 694 [26] BuildingSMART, IFC4 Design Transfer View Welcome to
695 buildingSMART-Tech.org (2016).
696 URL [http://www.buildingsmart-tech.org/specifications/](http://www.buildingsmart-tech.org/specifications/ifc-view-definition/ifc4-design-transfer-view/)
697 [ifc-view-definition/ifc4-design-transfer-view/](http://www.buildingsmart-tech.org/specifications/ifc-view-definition/ifc4-design-transfer-view/)

- 698 [27] BuildingSMART, Home Welcome to buildingSMART-Tech.org (2016).
699 URL <http://www.buildingsmart-tech.org/>
- 700 [28] US GSA, Information Delivery Manual (IDM) for BIM Based Energy
701 Analysis as part of the Concept Design BIM 2010 (2009).
702 URL [http://www.blis-project.org/IAI-MVD/IDM/BSA-002/PM_](http://www.blis-project.org/IAI-MVD/IDM/BSA-002/PM_BSA-002.pdf)
703 [BSA-002.pdf](http://www.blis-project.org/IAI-MVD/IDM/BSA-002/PM_BSA-002.pdf)
- 704 [29] T. Liebich, K. Stuhlmacher, M. Weise, R. Guruz, P. Katranuschkov,
705 R. J. Scherer, HESMOS D+ Additional Deliverable: Information Delivery
706 Manual Work within HESMOS, Tech. rep., © HESMOS Consortium,
707 Brussels, Belgium (2013).
708 URL [http://hesmos.eu/downloads/hesmos_additional-del_idm_](http://hesmos.eu/downloads/hesmos_additional-del_idm_final.pdf)
709 [final.pdf](http://hesmos.eu/downloads/hesmos_additional-del_idm_final.pdf)
- 710 [30] T. Liebich, K. Stuhlmacher, P. Katranuschkov, R. Guruz, N. Nisbet,
711 J. Kaiser, B. Hensel, R. Zellner, T. Laine, M. C. Geißler, HESMOS De-
712 liverable D2 . 1: BIM Enhancement Specification, Tech. rep., © HESMOS
713 Consortium, Brussels, Belgium (2011).
- 714 [31] C. M. Rose, V. Bazjanac, An algorithm to generate space boundaries for
715 building energy simulation, *Engineering with Computers* 31 (2) (2013) 271–
716 280. doi:10.1007/s00366-013-0347-5.
- 717 [32] J. T. O'Donnell, T. Maile, C. Rose, N. Mrazovic, E. Morrissey, C. Regnier,
718 K. Parrish, V. Bazjanac, Transforming BIM to BEM: Generation of Build-
719 ing Geometry for the NASA Ames Sustainability Base BIM, Tech. rep.,
720 Lawrence Berkeley National Laboratory, Berkeley, CA (2013).
721 URL <https://eetd.lbl.gov/node/51468>
- 722 [33] V. Bazjanac, A. Kiviniemi, Reduction, Simplification, Translation and
723 Interpretation in the Exchange of Model Data, in: 24th CIB-W78,
724 University of Maribor, 2007, pp. 163–168.
725 URL [http://cic.vtt.fi/projects/vbe-net/data/2007_Data_](http://cic.vtt.fi/projects/vbe-net/data/2007_Data_Simplification_@_CIB-W78_Maribor.pdf)
726 [Simplification_@_CIB-W78_Maribor.pdf](http://cic.vtt.fi/projects/vbe-net/data/2007_Data_Simplification_@_CIB-W78_Maribor.pdf)

- 727 [34] T. Maile, J. O'Donnell, V. Bazjanac, C. Rose, BIM-Geometry Mod-
728 elling Guidelines for Building Energy Performance Simulation, in: 13th
729 Conference of International Building Performance Simulation Association,
730 Chambéry, France, 2013, pp. 3242–3249.
- 731 [35] V. Bazjanac, Space Boundary Requirements for Modeling of Building Ge-
732 ometry for Energy and other Performance Simulation, in: 27th CIB-W78
733 Conference, Cairo, Egypt, 2010, p. 10.
- 734 [36] LBNL, Space Boundary Tool -Simulation Research (2013).
735 URL [http://simulationresearch.lbl.gov/projects/
736 space-boundary-tool](http://simulationresearch.lbl.gov/projects/space-boundary-tool)
- 737 [37] KIT, EnEff-BIM model check & EnEff-BIM converter (2016).
738 URL <https://download.building-lifecycle-management.de/>
- 739 [38] S. Ebertshäuser, P. von Both, Prüfung und Konvertierung von HVAC
740 ifcXML zu SimModel, in: J. Grunewald (Ed.), Proceedings CESBP - Cen-
741 tral European Symposium on Building Physics/ BauSIM 2016, Fraunhofer
742 IRB Verlag, Dresden, 2016, pp. 621–628.
- 743 [39] DIN V 18599, Energetische Bewertung von Gebäuden - Nutzungsrandbe-
744 dingungen, Klimadaten (2007).
745 URL <https://www.beuth.de/de/vornorm/din-v-18599-10/259376282>
- 746 [40] SIA, SIA 2024 - Standard-Nutzungsbedingungen für Energie- und
747 Gebäudetechnik (2006).
748 URL [http://shop.sia.ch/normenwerk/architekt/sia2024/d/2006/D/
749 Product](http://shop.sia.ch/normenwerk/architekt/sia2024/d/2006/D/Product)
- 750 [41] T. Chipman, T. Liebich, M. Weise, mvdXML - Specification of Standard-
751 ized format to define and exchange Model View Definitions with Exchange
752 Requirements and Validation Rules, Tech. rep., Model Support Group
753 (MSG) of buildingSMART International Ltd. (2013).
754 URL <http://www.buildingsmart-tech.org/downloads/>

755 accompanying-documents/formats/mvdxml-documentation/
756 mvdxml-schema-documentation-v1-1-draft

757 [42] BuildingSMART, IfcUnitaryEquipment (2017).
758 URL [http://www.buildingsmart-tech.org/ifc/IFC2x4/rc2/html/](http://www.buildingsmart-tech.org/ifc/IFC2x4/rc2/html/schema/ifchvacdomain/lexical/ifcunitaryequipment.htm)
759 [schema/ifchvacdomain/lexical/ifcunitaryequipment.htm](http://www.buildingsmart-tech.org/ifc/IFC2x4/rc2/html/schema/ifchvacdomain/lexical/ifcunitaryequipment.htm)

760 [43] BuildingSMART, IFC4 Add2 Documentation (2016).
761 URL [http://www.buildingsmart-tech.org/specifications/](http://www.buildingsmart-tech.org/specifications/ifc-releases/ifc4-add2)
762 [ifc-releases/ifc4-add2](http://www.buildingsmart-tech.org/specifications/ifc-releases/ifc4-add2)

763 [44] BuildingSMART, ifcDoc Tool Summary (2016).
764 URL [http://www.buildingsmart-tech.org/specifications/](http://www.buildingsmart-tech.org/specifications/specification-tools/ifcdoc-tool/ifcdoc-beta-summary)
765 [specification-tools/ifcdoc-tool/ifcdoc-beta-summary](http://www.buildingsmart-tech.org/specifications/specification-tools/ifcdoc-tool/ifcdoc-beta-summary)

766 [45] T. Chipman, IFCDOC Usage Guide (Version 3.8), Tech. rep., BuildingS-
767 MART International (2012).
768 URL [http://www.buildingsmart-tech.org/specifications/](http://www.buildingsmart-tech.org/specifications/specification-tools/ifcdoc-tool/ifcdoc-help-page-section/IfcDoc.pdf/view)
769 [specification-tools/ifcdoc-tool/ifcdoc-help-page-section/](http://www.buildingsmart-tech.org/specifications/specification-tools/ifcdoc-tool/ifcdoc-help-page-section/IfcDoc.pdf/view)
770 [IfcDoc.pdf/view](http://www.buildingsmart-tech.org/specifications/specification-tools/ifcdoc-tool/ifcdoc-help-page-section/IfcDoc.pdf/view)

771 [46] BuildingSMART, ifcDoc Baselines Welcome to buildingSMART-Tech.org
772 (2016).
773 URL [http://www.buildingsmart-tech.org/specifications/](http://www.buildingsmart-tech.org/specifications/specification-tools/ifcdoc-tool/ifcdoc-baselines)
774 [specification-tools/ifcdoc-tool/ifcdoc-baselines](http://www.buildingsmart-tech.org/specifications/specification-tools/ifcdoc-tool/ifcdoc-baselines)

775 [47] Y.-C. Lee, C. M. Eastman, J.-K. Lee, Validations for ensuring the interop-
776 erability of data exchange of a building information model, Automation in
777 Construction 58 (2015) 176–195. doi:10.1016/j.autcon.2015.07.010.
778 URL [http://linkinghub.elsevier.com/retrieve/pii/](http://linkinghub.elsevier.com/retrieve/pii/S0926580515001533)
779 [S0926580515001533](http://linkinghub.elsevier.com/retrieve/pii/S0926580515001533)