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A standardized approach to BIM and energy simulation connection

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BIM (Building Information Model) applications cover many areas such as quality control, monitoring, structural analysis and space management. BIM is also widely used as a basis for energy simulation as it contains most of the data needed for energy analysis. However, buildings feature multi-physics phenomena in which energy is only one aspect; therefore it is often needed to jointly perform different kinds of simulations and, to properly connect BIM to the related simulation environments and formats. In line with this concern, our research work focuses on the issue of heterogeneous multi-models interoperability for simulation. The aim is to devise an approach and to develop tools that can support and enhance connections between BIM authoring tools and simulation tools, covering various physical dimensions. To implement this approach, we propose to rely on some well-proven and focused standards from the Building Smart International consortium, namely the IDM (Information Delivery Manual) and the Model Views Definition (MVD). In this respect, this paper brings two contributions. The first is an in-depth review and discussion of the interoperability issues of the Architecture, Engineering and Construction (AEC) area, in particular since the advent of BIM technologies. The second is an account of the first results of our research work, focusing on the definition and implementation of a well-structured and standards-compliant approach to the generation of energy simulation models from BIM IFC (Industry Foundation Classes) models. This work entailed defining a mapping between the building elements as defined in the targeted simulation engine (the simulation engine of the French thermal regulation), and the corresponding IFC elements and attributes. As the IFC do not cover all the required elements for energy simulation, further enrichment of the IFC – either through ad hoc extension or through connection to complementary data sources – was defined and implemented.

Keywords: BIM/ IFC, Interoperability, IDM/ MVD, Energy Simulation, Collaborative Design

1 Introduction

In the Information Communication Technology (ICT) area, where various stakeholders from multiple domains are sharing and exchanging data through heterogeneous tools, interoperability is widely acknowledged as a major issue.

Data interoperability as defined by Shen et al. [60] is the ability to ensure that data generated by any one party can be properly interpreted by all other parties. Data interoperability allows for information exchange: it is the first step toward effective systems integration and collaboration.

Jim Steel [62] identified three interoperability levels in conformance with the KISS (Knowledge Industry Survival Strategy) interoperability classification framework [10]:

- File and syntax levels: File level interoperability is the ability of two tools to successfully exchange files. Syntax level interoperability is the ability of two tools to successfully parse those files without errors,
- Visualization level interoperability relates to the ability of two tools to faithfully visualize a model being exchanged,
- Semantic level interoperability relates to the ability of two tools to reach a common understanding of a model being exchanged.

The issue of interoperability is present in a lot of areas, as long as collaboration, interaction and data exchange are needed. This is particularly true of the AEC (Architecture, Engineering and Construction) area, where the evolution of the practices and the uptake of the Building Information Modelling (BIM) paradigm have intensified the need for collaboration between different stakeholders across many disciplines throughout the entire building life-cycle.

BIM is recent approach to design and document a building project, emphasizing data exchange and interaction between different domains. Van Berlo [67] makes the distinction between "big BIM" and "little BIM" [34]. “Little BIM" refers to a project limited to one application domain and using a unique (proprietary) software tool. “Big BIM" is when collaboration is established between multiple project partners. It is based on a pluralistic software environment where the different project stakeholders can collaborate by using different, heterogeneous, software tools. To summarize, the BIM, in a “big BIM” context, is a conceptual process in a collaborative work environment [26], where many stakeholders communicate through the use of diverse tools and exchange building data.

According to Merschbrock [46], BIM interoperability is one of the most important issues in the construction industry – this observation is confirmed by the extensive literature review presented in the subsequent sections. In particular, most of the authors emphasize that, to insure the three interoperability levels and facilitate information exchange, there is a need to standardize the BIM process and to define structured guidelines for its implementation. Many initiatives aimed at the definition of relevant standards that ensure data compatibility between models from different software tools through a common BIM data format. In this scope, the IFC (Industry Foundation Classes) from the BuildingSMART international consortium has drawn the interest of the AEC community and is likely to become the standard BIM language in a near future. The emergence of standard BIM data formats does not, however, brings a definitive solution to the interoperability issue. As shown in the first part section 2, the jury is still out – a large number of data formats is available, each coming with specific advantages and drawbacks. In addition, even the most well established standards still suffer from some limitations that hinder their relevance for business-specific applications. This is for instance true of energy simulation, as illustrated in the second part of section 2. Therefore, in order to widen BIM standards applicability, it is still necessary to resort to ad-hoc extension mechanisms, as described and discussed in section 3. Fortunately, some standards come with powerful extension and adaptation frameworks. This is e.g. the case of IFC, with the IDM (Information Delivery Manual) and the MVD (Model Views Definition), which we have used to enable BIM and energy simulation connection. Section 4 gives the results of this study and discusses the limitations of the approach.

To summarize, this paper proposes a critical review and a case study of BIM interoperability through the specific prism of BIM and energy simulation connection. The first section (section 2) outlines the base BIM data formats and interoperability support and gives an account of the limitations with respect to BIM and energy simulation connection. Section 3 then critically reviews the approaches to BIM interoperability enhancement, with a focus on energy simulation. At last, section 4 gives an account of a study lead to evaluate the relevance and applicability of standard BIM extension approaches to the particular case of energy simulation. The case study targets the connection of Industry Foundation Classes and the standard simulation engine of the French thermal regulation. At last, a conclusion reminds the contributions of the paper and gives some perspectives.

2 Interoperability in BIM

In this section, we first outline the available BIM data formats standards, before highlighting their limitations with respect to connection to energy simulation.

2.1 Open and proprietary BIM exchange data format

A wide range of BIM exchange data formats are available, some of which are open (e.g. the IFC), some others are proprietary and relate to commercial BIM authoring tools. A large part of the open standards are based on the EXPRESS [32] data language and on other open standards – e.g. the eXtensible Markup Language (XML). The most known EXPRESS based standards are STEP, CIS/2 and IFC.

– *STEP***:** ISO 10303 known as STEP (Standard for the Exchange of Product model data) defines product data, some of which relates to geometry [70]. It addresses the problem of exchanging product information between dissimilar applications through the product lifecycle. It has been used in several application domains to support collaborative engineering [54]. It is considered as an inspiration source for IFC (Industry Foundation Class) and is used as a basis by all the major building data model specifications (IFC, ISO/PAS 16739, CIS/2 [21]).
– *CIS/2***:** (CIS/2), CIMsteel Integration Standard, Version 2, is a model based on ISO-STEP technology widely adopted within the steel construction industry [21]. It is one of the earliest product models that have been widely adopted by industry that supports exchange across a broad set of heterogeneous applications.
– *IFC***:** (Industry Foundation Class) is an open source object-oriented standard schema for the AEC industry that was developed by the International Alliance for Interoperability (IAI). The purpose of IFC is to facilitate the exchange of information used by AEC professionals during the building life-cycle [75]. It is intended to enable interoperability between building information modelling software applications in the AEC/FM (Facility Management) industry [36]. Nowadays, numerous proprietary software support IFC through dedicated import / export functions: Autodesk, Bentley system, Graphisoft, Nemetschek, Solibri, Tekla, Archimen group, Vector works, [64] etc…

Interoperability is also often achieved through the use of eXtensible Markup Language (XML) [64]. The XML is an open standard widely used to facilitation the structured exchange of information. The following interoperability data formats have been developed based on the XML:

– *CityGML***:** The CityGML schema is used for geo-spatial data representation. In addition, IFC data can be represented with the ifcXML schema.
– *landXML***:** LandXML specifies an XML file format for civil engineering design and survey measurement data.
– *gbXML***:** The gbXML (Green Building XML) schema is used for describing data relating to the building energy efficiency of the facility and its impact on the environment
– *aecXML***:** The aecXML schema is used for depicting all building data in design, engineering and construction disciplines. It includes XML schemas to describe information specific to the design, construction, and operation of buildings, plants, infrastructure, and facilities. [19]

- *ifcXML*: In addition to the IFC-EXPRESS specification an ifcXML specification is published as well [17] (since the IFC2x release). ifcXML is the XML version of IFC. It provides XML language bindings to the IFC EXPRESS schema [36].

Otherwise, different BIM proprietary tools use their native data formats. The most famous ones are from Autodesk, which allow the user to design with parametric modelling and drafting elements. The main proprietary formats are:

– *RVT* (Revit Autocad): stands for Autodesk Revit Architecture project file. It is the native format for Autodesk Revit.
– *DWG* (DraWinG Autocad) is the native file format of Autodesk's AutoCAD software
– *DGN* is the native file format in Bentley Systems. It is compatible with AutoCAD
– *DXF* (Drawing eXchange Format) is an open file format developed by Autodesk

Not only design tools are involved in the exchange process but also other BIM applications that cover areas such as quality control, monitoring, structural analysis and space management. BIM is also widely used as a basis to define and / or generate the building simulation models. One critical issue is in particular to enable effective and reliable connections between BIM and energy simulation tools, the majority of which relies on specific, non-standards-compliant formats. The following subsection focuses on this issue, highlighting the limitations of the two main standards used in the scope of BIM and energy simulation interoperability.

2.2 Limitations of BIM standards for energy simulation applications

Energy simulation plays an important role in building design by predicting energy performance, in order to support the optimization of design choices throughout the building design process. However, simulation effectiveness is still hindered by interoperability shortcomings between design tools and simulation tools [47]. To ensure interoperability between BIM and simulation models, the two most relevant data formats currently used in the AEC industry are IFC and gbXML. A detailed description of IFC and gbXML, and a comparison between them, can be found in [5] and [6].

gbXML (Green Building XML) allows for the description of building geometry and its properties, specifically for energy simulation purposes, thus easing data exchange between building models and analysis tools. The format features a well-organized information structure in which building data are stored along different levels of detail. For illustration purposes, an extract of a gbXML model is given below. This example well illustrates the hierarchical structure of gbXML, ranging from campus, building, zone, surface, openings and construction type, and related parameters.

The gbXML format also allows specifying the properties and the features of the neighbouring environment, thus enabling to properly take into consideration the context in which the construction is set, beyond the building itself. This is a distinctive feature of this format that has been designed on purpose with the goal to ease the design of green and environmental-friendly buildings.

```
<gbXML>
<Campus id="cmps-1">
  <Location>
    <Name>User Defined</Name>
  </Location>
  <Building id="bldg-1">
    <Space id="sp-101">
      <Name>101</Name>
      <Area>100</Area>
    </Space>
  </Building>
  <Surface id="su-sp-101" surfaceType="SlabOnGrade">
    <AdjacentSpaceId spaceIdRef="sp-101" />
    <RectangularGeometry>
      <Azimuth>0</Azimuth>
      <Tilt>180</Tilt>
      <Height>4.2</Height>
      <Width>10</Width>
    </RectangularGeometry>
  </Surface>
 </Campus>
 <Zone id="zone-Default">
  <Name>Default</Name>
 </Zone>
</gbXML>
```

The gbXML format also allows specifying the properties and the features of the neighbouring environment, thus enabling to properly take into consideration the context in which the construction is set, beyond the building itself. This is a distinctive feature of this format that has been designed on purpose with the goal to ease the design of green and environmental-friendly buildings.

IFC has become the reference standard data format for the building industry. Developed by BuildingSMART, it has been kept open and free, and to our knowledge is currently the only format implemented by most of the CAD tools. It has been specified with the purpose to play that “bridging role” between formats, enabling data exchange and interoperability among tools. Given its object-oriented paradigm, that allows representing all the elements of a building as objects with properties and references to other objects, the IFC format can be easily managed and understood by various tools. An excerpt of a building model in the IFC format is reported thereafter, which includes the IFCProject with the context information and then the hierarchically structured project elements (IfcSite, IfcBuilding, IfcBuildingStorey). Building components are then defined (IfcWall(StandardCase), IfcOpeningElement, IfcWindow, IfcDoor) together with their relationships.

```
#1=IFCPROJECT('3CNwCeY6n5Y9TFdGcKyi2B',#2,",$,$,$,(#4),#5);
#4=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.E-005,#19,#20);
...
#8=IFCSITE('3CNwCeY6n5Y9TFdGcKyi29',#2,'Default',$,",#47,$,$,.ELEMENT.,(48,51,23,999633),(2,21,3,553905),0.,$,$);
...
#137=IFCBUILDING('3CNwCeY6n5Y9TFdGcKyi2A',#2,",$,$,#138,$,",.ELEMENT.,$,$,#321);
```

```
#138=IFCLOCALPLACEMENT(#47,#324);
...
#371=IFCSPACE('0SElRwRi94mwmw5daN5l_Y',#2,'2',$,$,#583,#196,'Pi\X\E8ce',.ELEMENT.,.SPACE.,$);
#372=IFCRECTANGLEPROFILEDEF(.AREA.,$,#739,2.50000000000001,2.98);
...
#580=IFCBUILDINGSTOREY('3CNwCeY6n5Y9TFdGbh3JqR',#2,'Niveau 0',$,$,#322,$,'Niveau 0',.ELEMENT.,0.);
#581=IFCBUILDINGSTOREY('3CNwCeY6n5Y9TFdGbh3JWD',#2,'Niveau 1',$,$,#323,$,'Niveau 1',.ELEMENT.,3.);
#582=IFCPROPERTYSET('2Ps44h3395Peo5HKYi7kZB',#2,'Pset_BuildingCommon',$,(#1671,#1672));
#583=IFCLOCALPLACEMENT(#322,#1673);
...
```

IFC and gbXML are efficient to ensure data interoperability in a building project, as shown by a survey from Bahar et al. [6]. This survey characterizes the interoperability level among the tools, by specifying the input and output formats of each surveyed tool. It can be easily noticed that the most common used formats are IFC and gbXML. However some limitations remain. For instance, very few applications support heating, ventilation, and air conditioning (HVAC) information generated by gbXML [49].

Referring to the KISS interoperability levels, we can notice that the use of IFC will successfully provide file and visualization level interoperability, as IFC is supported by many tools allowing the import/export of IFC data file. However with respect to the usage in the energy simulation domain, it does not provide semantic interoperability. For instance, the IFC does not allow the specifications of all elements required to express HVAC systems, which represents a big limitation for its application in the energy simulation domain.

While being a well-known problem in the AEC industry, the most recent version of IFC , IFC 4, has not yet overcome this issue [56]]. So, in order to overcome the inherent limitations of IFC model, many researches aim to improve it by extending it or with the use of the semantic web technologies as a mechanism to obtain a flexible data modelling. In the next section, we give an account of these methods to enhance interoperability in BIM.

3 Methods to enhance BIM interoperability

IFC is central in developing construction projects, but it sometimes lacks information. To overcome this limitation, it is often required to collect additional data from external sources. This ensures multi-model domain collaboration and allows for exploiting third party data. However, there are some alternatives to add more flexibility and enrichment to the building model, in particular with the IFC model. The first one is to rely on the extension mechanisms available with the standard. The second one is to enrich the semantics of the meta-model through ad-hoc methods.

3.1 Enhancing BIM interoperability through model extension

IFC describe most of the building elements and their properties. However, it is sometimes required to extend the modelling scope and to use external data sources. We give below a summary of the different options available to extend the IFC.

As a first solution, Liebich et al. [38] propose an approach for model evolution; it consists of the extension of BIM model by adding new concepts, attributes and relations. With this method, one can add to the BIM model the needed external information by integrating them into the standard data model specification. However, this means that it is required leveraging the standard itself, which requires significant effort and time. Indeed, according to Liebich, this approach has many drawbacks. Adding new elements in the model requires the development of new concepts, attributes and relations and takes a considerable time. Also, the standard will include more information, will become more complex and gradually becomes less manageable. As a result, this approach shall be favoured case for the cases where long-term adaptations are implemented, with a wide consensus of practitioners.

Another solution consists in the extension of BIM data by the exploitation of existing interfaces in the data model [38][38]. The IFC model actually features many prebuilt extension capabilities through subclasses like "IfcRelathionship" [16], "IfcProxy" [15], "IfcPropertySet" [14]. Such approaches offer more flexibility, allowing the model extension by using available IFC concepts. For example, the IfcPropertySet can be attached to any kind of elements with a key-value and thus enable the extension of their attributes. In addition, the IFC schema features an IfcProxy object to describe any objects not defined by the schema. For example, in the case of landscaping, there is no IFC construct for trees or shrubs, so these are often included (with geometries) as IfcProxy objects [62, 62]. Also, the IfcRelationship extension, which represents relations between IFC objects [22], brings additional extension capabilities through the possibility of turning the relationship between two classes into an object [71]

In the same flavour, the InPro project [69] resorted to property sets and proxy elements to be able to deal with exchange requirements that could not be handled by plain IFC (e.g. client requirements management, cost estimation and new approaches for BIM-based scheduling). Yang [72] also presents a method for IFC-compliant design information modelling and sharing thanks to IFC technology and IFC property set (Pset) extension mechanism. In this approach, a Pset is assigned to the object “entrance door”, in order to add additional properties like the door colour, and to precise the door type (e.g. fireRatingDoor or externalDoor). An illustration in this paper [72] introduces the use of Psets and their association with a door object model. A similar approach is found in the paper of Thomas Froese [24], used in his project different IfcPropertySet in order to facilitate decision making in the selection of materials. An interaction scenario is described, in which the designer is assigned a “design requirement” Pset and the supplier an “available” Pset. Each party may this way specify her requirements. In the scope of the PLUMES project [55], because of the IFC limitations, the consortium resorted to its enrichment by adding thermal properties of HVAC systems using IfcPropertySet mechanisms. Also, Liu et al. in their paper [40] advocate the extension of the quality management and security management information in construction. According to them, “the propertyset extension is flexible and simple, unlike the IFC schema extension which is laborious and time-consuming”.

This extension approach is easy, fast to implement and do not make changes on the standard model. As a result, it is frequently used to flexibly extend the IFC model without impacting the standard itself. But still, a drawback remains. Regardless of the extension approach chosen, extended IFC model still lack semantic information. Many researchers therefore advocate semantic enrichment of the model to supplement data models extensions.

3.2 Enhancing BIM interoperability through IFC semantic enrichment

According to the KISS hierarchy IFC does not provide for semantic interoperability [62]. In order to overcome this limitation, many researches have focused on the semantic enrichment of IFC.

- **IFD as an extension mechanism**

  To ensure interoperability, BuildingSMART proposes a flexible library called IFD (the International Framework for Dictionaries), with the possibility to extend the IFC schema as needed. IFD works as a supplement to IFC. IFD can express ontologies but is not in itself an ontology [13]. It adds more flexibility to the IFC model, by linking the IFC concepts with various databases. It allows for extending the vocabulary and enriching relationships in the IFC model. According to the BuildingSMART initiative, IFC "defines the format for information exchange", while the International Framework for Dictionaries (IFD) informs about how to "interpret the information exchanged" [8].

  IFD includes concepts expressed textually, in natural language. For instance, a concept may be expressed using different names: the word "dør" in Norwegian, can be translated to "door" in English. But according to the concept, "dør" should rather be translated to "door set". Also, IFD provides synonyms, acronyms and definitions: one concept can have multiple names in the same language and can be expressed in different ways. Indeed a concept can be expressed by a set of names (definitions) or with relation a concept to another one [13]. For example, all translations of the term "door" (Porte, Porta, etc) will refer to the same underlying entity. These concepts are labelled with a Global Unique Identifier (GUID) that is used to refer to the same concept from all instances.

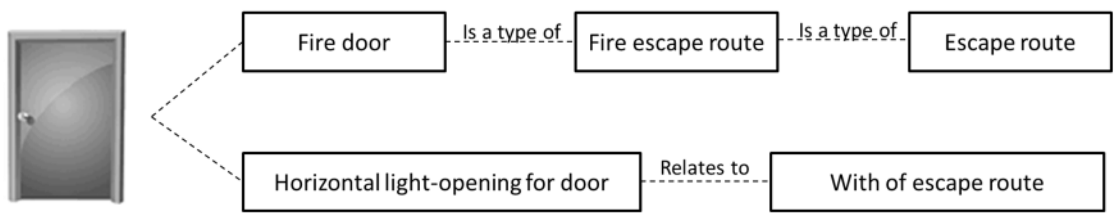

Figure 1 Ifd concepts [13]

  In addition, some researches work on expanding the capabilities of IFD. For instance, Mahdavi et al [44] introduce their protorype called the "SkyDreamer" implemented with Semantic Web technologies using an extension of an IFC entity to enrich a building model expressed in IFCXML format. The IFD semantic repository used in this prototype can be extended to cover additional building elements with the ability to communicate using web services. According to Zhang et al. [76], three factors are actually needed for an efficient BIM information exchange: IFC as an exchange format, IDM to specify which information to exchange and when to exchange it and, IFD for a standardized understanding of the information exchanged. They built a prototype of an IFD library based on IFC3 in order to define the concepts of the IDM functional parts. IFD was used as a bridge between user-level collaboration and machine-level interoperability.

- **IFC and Ontology based enrichment**

  One strong trend is the semantic enrichment of IFC thanks to ontologies, i.e. “formal representation of an abstract, simplified view of a domain that describes the objects, concepts and relationships between them that holds in that domain” [27]. Most of the related approaches rely on the Semantic Web [4] [12] [[33] [[66] [78][78]. Semantic web is used in diverse application domains. It is an approach for inter-linking data expressed in a standard format, reachable and manageable by automated tools. Web Ontology Language (OWL) is the formal ontology language developed for the Semantic Web. It is a family of knowledge representation languages for authoring ontologies. The languages are characterized by formal semantics and RDF/XML-based serializations for the semantic Web [25].

The main components of the semantic web are:

- *RDF* (Resource Description Framework) is a model for representing data about resources in the web,
- *OWL* is the Web Ontology Language, a standard to write semantics,
- *SPARQL* is a query language for RDF,
- *LinkedData* refers to a style of publishing and linking structured data on the Web [9].

To fully exploit the multidimensional aspect of BIM, researchers have attempted to apply semantic web in the construction industry. Many research groups advocate using a connection between the IFC standard and semantic Web and the development of an ontology extension to IFC [65], in which IFC models are converted to RDF graphs and, where functionalities are added through RDF-based semantic annotations using [64].

In this scope, some studies even target the integration of ontologies with BIMs. As a use case, Venugopal et al [65] propose an ontological approach to Building Information Model exchanges in the Precast/Pre-stressed Concrete Industry. The aim of their research is to create an ontological framework, which makes the IFC definitions more formal and consistent. They claim that this approach makes model view specifications unambiguous and reusable, thereby reducing the development time of model views.

In the same area, Yang and Zhang [73] propose extensions to the IFCs to map them to ontologies to improve the semantic interoperability of BIM models; An object CAD based, IFC compliant, and ontology enabled semantic interoperability approach has been devised, and software developed, for capturing and reusing interoperable, semantics-rich information with building design objects. And Si and Wang [61] propose the construction of an architectural ontology based on IFC with the building of the concepts, properties and the relationship between the concepts of the ontology. Also, Zarli et al. give in [74] an outline of a formal ontological approach of conformance models for regulations in construction. To analyse the IFC model redundancy and/or insufficiency for conformance checking reasoning, an intermediate RDF-based model, semantically enriched has been used [1]. For the same purpose, Dibley et al [20] propose an ontology development process to deliver an intelligent multi-agent software framework (OntoFM) supporting real time building monitoring.

More and more projects are using RDF and OWL technologies to add knowledge management functionality [64]. For example, InteliGrid project [43][43], the SWOP project [11] and the Sydney Opera House facility management model [59] where the IFC model is transformed using an IFC-OWL converter [58]. Beetz et al. also propose the conversion of the EXPRESS schema to OWL ontology [7]. They propose an OWL ontology called ifcOWL derived from the EXPRESS schema.

Additional studies aims at the integration of ontologies with BIMs [37][42] [65] [77]. For example, Abanda et al. in their paper [2] highlight the weakness of IFC, gbXML and COBie, and discuss the advantage of the use of semantic web by converting IFC to RDF. They explore the relationships between linked open data and building information modelling. Other researches propose the creation of an ontology, like [23] which proposes ontology architecture models highway concepts into six major concepts including project, process, product, actor, resources and technical topics (attributes and constraints).

Nowadays several open source converters for Semantic Web formats are available. XSD2OWL provides transformation of an XML Schema into an OWL ontology and XML2RDF enables transformation of XML into RDF (ReDeFer project). Converters are also developed to transform IFC standard into RDF or OWL ontology [53].

3.3 Discussion

To summarize this section, model enrichment can be made mainly in two ways: either through (meta) model extension or through semantic enrichment.

We reviewed the first approach essentially focusing on the IFC model and its extension mechanisms. Two main options are available: extending the standard itself, or using ad-hoc or standardized extension mechanisms. The evolution of the standard is actually an effective and sustainable solution, but it is a heavy task, time consuming and which leads to complex models. The model data extension using existing interfaces in the model offers more flexibility. It is simple and fast to implement and does not imply changes on the model. This solution is widely used, especially relying on the PropertySet extension, which, as we saw earlier through several example, is the most widely used. Still, the disadvantage of this method is the fact that it doesn’t provide any semantic depth. The propertyset and proxy elements are only able to extend the scope of IFC without making any change on the schema. Also, the extension is local and requires the implementation of agreements if we need to share it with other CAD software.

In order to address this lack of semantic, many approaches propose the semantic enrichment of the IFC model. In this context, BuildingSMART provides the IFD as a reference library to complete the IFC model and enhance the semantics of the information being shared. It is a multi-concept approach, which offers multilingual property sets [69]. But this solution can only be used as a supplement to IFC, extending its capabilities for a particular use, without enabling any connection with external data sources.

To enhance IFC semantic, many researches advocate the conversion of the IFC model into an ontology language and, to complete it with additional, external, information. The advantage of this proposition is the enhanced flexibility of semantic web as the OWL and RDF are more expressive than the EXPRESS language. Moreover, many conversion tools are already implemented: the IFC to RDF conversion service is currently developed [48], [53] and the EXPRESS to OWL conversion rules are already defined. Other conversion tools exist such as the E-OWL which is the semantic Web implementation of EnergyPlus Data Model [41].

We can notice through the multiple examples seen earlier, that the use of semantic web extension is the most popular solution despite its drawbacks. The main issue is the considerable time needed for the conversion from IFC to an ontology language and, the necessity to maintain and evolve the conversion tools. There are also some minor issues with the conversion. For instance, Schevers [58] states that, in IFC to OWL conversion, "converting local entity attributes to global slots may cause problems when EXPRESS entities define attributes with the same name".

Table 1 gives a summary of the review and the related discussion.

Table 1 Approaches for model enrichment

	Approaches to interoperability enhancement			
	Model Extension		**Model semantic enrichment**	
	Model evolution *By adding new concepts to the standard (Object, Relation, Attribute)*	**Model data extension** *By the use of existing interfaces in the standard model (PropertySet, Proxy…)*	**IFD** *By the use of the IFD library as a complement to IFC*	**Ontology** *By the conversion and enrichment of IFC model using semantic web technologies*
Advantages	- Wider implementation - Sustainable solution - More impact	- Easy and quick to implement - Widely used - No change to the standard	- Offers a dictionary (multi-concept, multi-lingual) - Standard compliance	- Several conversion tools exists - Better expressiveness
Drawbacks	- Implementation time - Complex models - No expertise on some external data - No semantic	- Local extension (CAD tool import/export) - No semantic	- Only enrichment (no extension)	- Conversion time to RDF/owl - Tool maintaining
Related work	- BuildingSmart	- Liebich (2012) - Yang & Zhang - Yang (2003) - Froese(2003) - Robert et al. (2012) - Liu & Zhang (2012) - BuildingSmart	- BuildingSmart initiative - Mahdavi et al. (2008) - Zhang & Lin(2012)	- Beetz (2009) - Zhang & Isse (2011) - Yurchyshyna & Zarli (2009) - El Mekawy (2010) - Venegopal (2012) - Si & Wang (2012)

4 Toward a Building Simulation Model

The IFC standard still features some limitations that hinder its effectiveness for a proper energy simulation. IFC models are often incomplete and require exporting building design data from additional sources and to enrich the source model.

In order to achieve interoperability and improve the efficiency of BIM authoring environments, Building Smart, the International Alliance for Interoperability (IAI), proposed a methodology called IDM (Information Delivery Manual)/MVD (Model View Definition) to define and structure the exchange [51].

The mapping of building geometry to energy model is a wide area of research. For example [29] proposed an IFC to EnergyPlus transformation. Also, the Simergy project [50] is about transforming BIM to BEM (Building Energy simulation Model) with a mapping process between ArchiCAD and EnergyPlus. Some researchers also aim at leveraging the design model through adequate extensions, such as [18], which outlines a methodology that extends the IFC schema with energy concepts.

4.1 IDM MVD methodology

To facilitate model exchange, BuildingSMART has proposed a dedicated methodology: IDM/MVD (Information Delivery Manual / Model View Definition). These two mechanisms enable to specify how data exchanges between different applications can be performed.

First, the Information Delivery Manual (IDM) helps to document and structure information exchange between the communicating models. It specifies the involved actors, which information exactly is needed and when the exchange is required. It is composed by a *Process Map* describing the exchange process (interactions between the involved actors), a set of *Exchange Requirements (ERs)* defining the exchanged information, leading to and *Exchange Requirements Model (ERM)* organizing the ERs into exchange concepts.

The Model View Definition (MVD) is a subset of the IFC schema describing the exchange in one or more related IDMs. It contains first an *MVD overview* describing the addressed IDM, then a set of *MVD diagrams*, defining the MVD concepts to use for the exchange and finally a *concept implementation Guidance* defining the IFC entities to use. All these components are intended to specify a subset of the IFC model corresponding to the considered exchange scenario.

Figure 2 describes the IDM / MVD methodology flow. During the IDM process, the first step consists in the definition of the actors and their roles; once defined the actors, the specification of their tasks is needed. This will lead to the extraction of the interactions and identification of the set of exchange requirements (ERs). An exchange requirement (ER) describes all details of the requirements to guarantee a successful exchange. Then, the MVD process defines the views extracted from the IFC model that respond to the user's need.

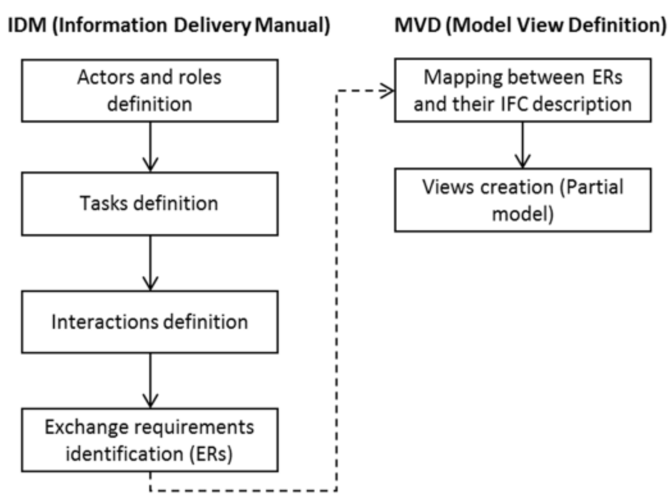

Figure 2 IDM/MVD Process

In the literature, there are many applications of the IDM/MVD methodology. For instance, the European project HESMOS for the energy management of an office building during the operation phase [35][35], proposes an extension of the IDM/MVD methodology consisting of: (i) the provision of a subschema generator to help modellers and to reduce model development time; (ii) the provision of a multi-model view generator and an object selection service in order to facilitate end user operations on the model.

Also, the InPro project [69] proposes a definition of business processes supported and designed by a shared BIM, including an example of a process map that presents the exchange requirements across the different actors. Other case studies of IDM application are also available in [52], [68], [3].

Drawing our inspiration from the aforementioned works, the purpose of our study is to apply the IDM process to IFC BIM and energy simulation connection. To this end, we rely on the COMETH simulation engine developed by our partner CSTB (the French Scientific and Technical Centre for Building). Our aim is to enable for the reliable generation of COMETH input models from IFC models relying on IDM and MVD.

4.2 An extended MVD for energy simulation

In general, an energy simulation tool aims to predict the energy performance of a building with the objective to provide the designer with all the necessary information for a building design that will offer optimal thermal comfort. There are many simulation tools on the market, of various kinds (commercial, free, regulatory) and relying on various simulation paradigms (zonal, nodal, Computational Fluid Dynamics…). However, the required input data of simulation tools for energy analysis are usually the following: building structure (geometry, spaces/thermal zones, building orientation, building construction, building usage), HVAC system requirements (heating, lighting, ventilating and air conditioning system) [6]; weather data and other simulation engine-specific parameters, such as the period of the simulation, have to be added. Output results generally include the building thermal performance, and an overall estimation of energy use and related monetary cost. This general scheme is outlined in Figure 3.

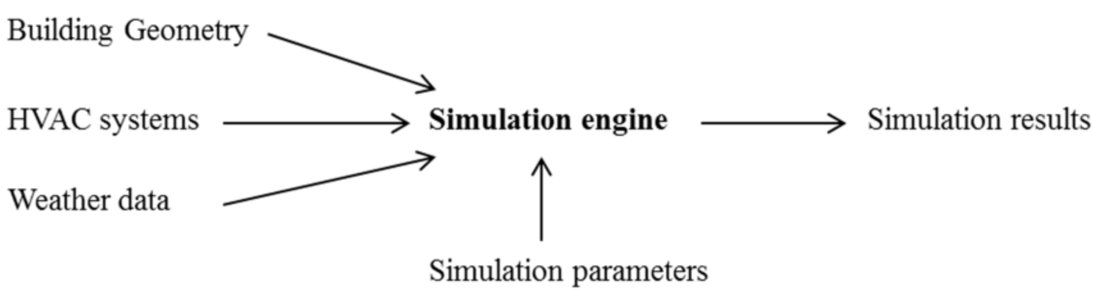

Figure 3 Input/output data of thermal simulation engine

Our work relies on COMETH, a simulation engine developed at CSTB since 2009. COMETH stands for COre for Modelling Energy and Thermal Comfort. It allows to calculate heat demand, to specify a ventilation model, a lighting model and the management of the openings / fenestrations of the building. It is composed three main models: thermal, ventilation and lighting model (see figure 4). The models include the description of the HVAC equipment deployed in the building. As a result, it computes the building's energy consumption at an hourly time step. In order to allow for collaborative developments to enable co-simulation, a COMETH-related ontology has been developed [28].

Input data for the energy simulation always need to be particularly accurate; provided information mainly consists in the building geometry and orientation, HVAC systems, project location (weather data) and simulation parameters. The typical outputs for the simulation are energy/thermal analysis, lighting analysis, acoustics and cost analysis [45].

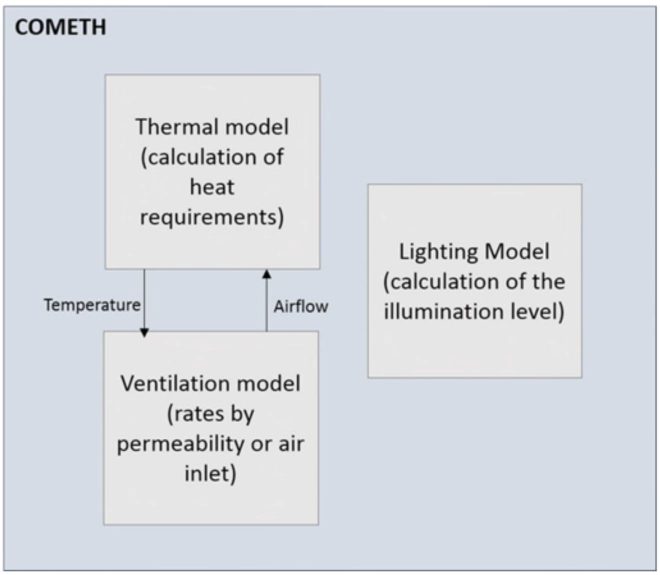

Figure 4 COMETH models

COMETH models are divided into different elements: building elements, distribution elements, lighting, exterior, emission system, heat system, photovoltaic system and ventilation (Table 2).

Table 2 COMETH elements

COMETH	System decomposition
	Building elements
	Distribution elements
	Lighting
	Exterior environment
	Emission system
	Heat generation system
	PV system
	Ventilation system

In order to apply IDM to IFC – COMETH connection, four main deliverables have to be developed: 1) a document defining the process participants, information and format to be exchanged and for what purpose, 2) the process map using BPMN templates describing the business processes through a graphical notation, 3) the exchange requirements document including all the exchanged information identified in the process map, and 4) a series of entity relationships diagrams ERM developed for each high level object in the information exchange.

- **Process map**

This is the first step in the IDM; it focuses the illustration of the process map. For illustration purposes, Figure 5 describes the process map for energy analysis. We can distinguish three actors: the design team, the client and the analysis team. The process starts with a concept design BIM that needs to be prepared and exported for energy analysis. At this level, we focus our interest on the exchange requirement from design to energy analysis called "ER BIM to Energy Analysis". This exchange requirement will be passed on to the analysis team in order to evaluate the energy performance results.

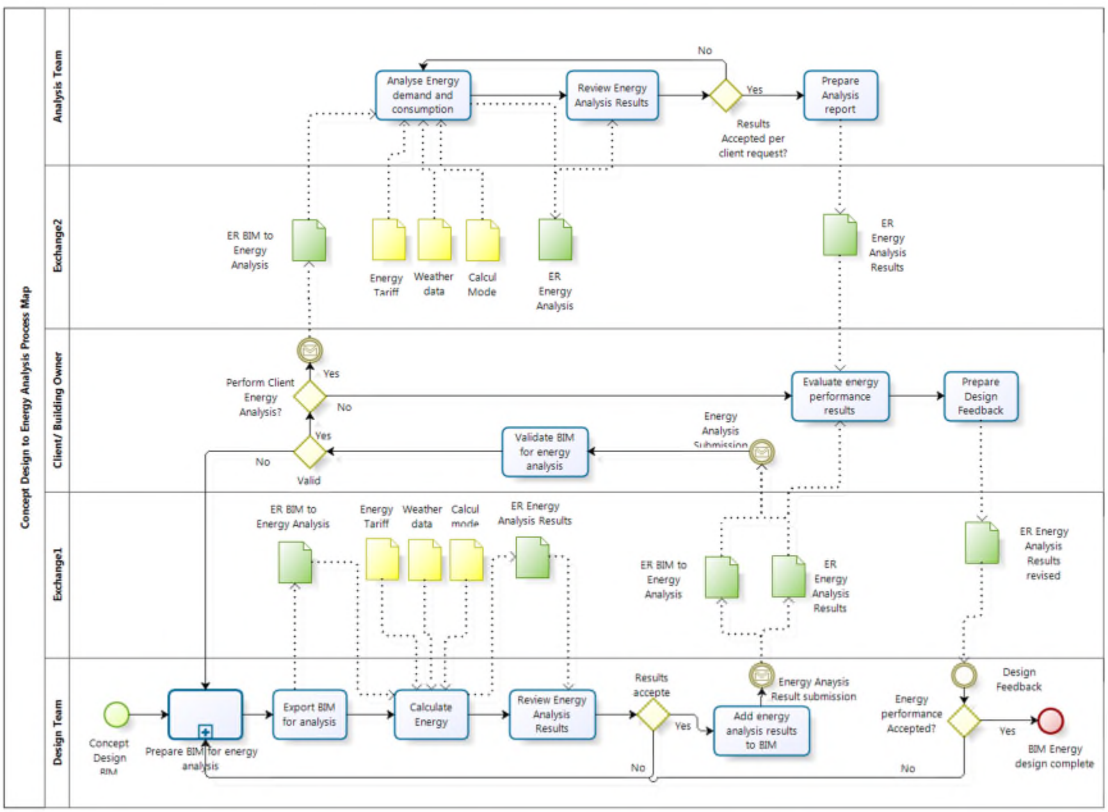

Figure 5 The Energy Analysis Process Map

- **Model decomposition**

The second step consists on the decomposition of the extracted exchange requirement “BIM to Energy Analysis” by specifying the required user inputs. The ER “BIM to Energy Analysis” contains the geometry; it aims to prepare BIM to energy analysis and simulation. It also includes the energy related materiel, location and climate data. The following table (Table 3) summarizes the elements needed for exchange.

Table 3 Exchange requirements BIM to energy analysis

Requirements	Description
User Input	building structure, energy related equipment, space data, site data
Building structure	spaces (geometry, space quantities, thermal requirements, lighting requirements, air quality requirements, space occupancy and usage, technical equipment, opaque components and transparent components,
Energy related equipment	mechanical ventilation, heating system, hot water system, cooling system, lighting system, photovoltaic system,
Space related	building envelope,
Site	building location, weather data. surrounding area, solar radiation

The exchange requirements are organized as follows:

- Building structure elements, describing the building geometry: building spaces, thermal bridges, space occupancy, opaque elements (wall), transparent elements (door, window)
- Building HVAC related requirements: thermal requirements (heating, cooling), lighting requirements, aeration requirements, natural ventilation requirements
- HVAC equipment: mechanical ventilation, heating system, hot water system, lighting system, photovoltaic system,
- Site and exterior environment: building location, weather data.

The next step consists in the decomposition of these requirements. For example, the HVAC equipment will be decomposed according to the required inputs in the simulation engine. Our target environment is COMETH, which describes a ventilation system, a heat generation system, lighting and photovoltaic system. Table 4 summarizes some of the components of each system.

Table 4 HVAC components

COMETH System	Components
generation (heat) system	boiler, cooling tower, pumps
ventilation system	Fans
distribution elements	Pumps
photovoltaic system	photovoltaic panel
lighting system	…

- **Mapping of the Exchange Requirements to IFC:**

This subsequent step aims at delivering the ER table, which details all components used in COMETH to perform the energy simulation and their mapping with the correspondent IFC object classes and their properties (Pset).

TTable 5 summarizes a subset of the IFC elements, which describe the geometry and represent some HVAC systems/components.

Table 5 Exchange requirements with IFC mapping

Category	Element	Correspondent IFC elements/ property set
Building Geometry	Building elements	IfcBuilding, IfcBuilding.name + Pset_BuildingCommon
	Spaces, occupancy	IfcBuilding + Pset_BuildingCommon, occupancyType IfcSpace +Pset_SpaceOccupancyRequirements, occupancyType
	Building opaque components	IfcWall, IfcSlab, IfcRoof, IfcColumn, IfcBeam, IfcRamp, IfcStair
	Building transparent components	IfcOpeningElement Eg. IfcDoor, IfcWindow, IfcCurtainXall
HVAC Requirements	Thermal requirements	IfcBuilding + Pset_SpaceThermalRequirements,AirConditioning
	Lighting requirements	IfcBuilding + Pset_SpaceLightingRequirements, Illuminance + Pset_SpaceLightingRequirements, ArtificialLignting
	Natural Ventilation requirements	IfcSpace, IfcSpatialZone, IfcZone, IfcSpaceType + Pset_SpaceThermalRequirements, NaturalVentilation IfcDistributionSystem + Pset_DistributionSystemTypeVentilation
HVAC System components	Mechanical ventilation system	IfcDistributionSystem.PredefinedType = VENTILATION IfcFan, IfcFanType + Pset_FanTypeCommon
	Hot water system (Boiler)	IfcBoiler, IfcBoilerType + Pset_BoilerTypeCommon IfcDistributionSystem.PredefinedType=DOMESTICHOTWATER IfcPump IfcCoolingTower, IfcCoolingTowerType
	Lighting system	IfcBuilding + Pset_SpaceLigntingRequirements, Illuminance
	Photovoltaic system	IfcSolarDevice

- **Extension / enrichment of IFC, proposition of property sets:**

While IFC 4 is more extensive than the previous version, it still features limitation regarding energy elements description [56]]. In Table 4 we draw some of the properties needed in COMETH and that IFC 4 do not cover.

Table 6 A subset of IFC shortcomings with respect to HVAC systems specifications in COMETH

	Elements to add
Mechanical ventilation system	• Maximum Flow Rate • Coefficient of singular loss
Hot water system (boiler, pump, coolingTower)	• Nature of the boiler to determine the default loss coefficient • Thermostat Management type of the boiler • Electric power of cooling towers • Maximum allowed temperature (resp. minimal) of air in the output/upstream source in cooling mode • Water temperature at the output of the tower • Pump's power loss
Lighting system	• Control mode of lighting • Total power of equipment and handling devices of artificial lighting in the room
Photovoltaic system, Solar sensor	• PV solar inverter efficiency curve • Temperature coefficient of the peak power • Number of sensors

Taking as an example the boiler (Table 7), we can notice that even with improvements in IFC4, it is still not expressive enough to describe boiler properties. We need to complete the list of property set by adding new one following our needs (or to make a reference to a complementary external model).

Table 7 ER table of the boiler component

Components	Unit	Type	IFC elements and properties
Function		Int	
Hot water production characteristics		String	
Max temperature	°C	Double	IfcBoiler + IfcPropertySingleValue (Pset_BoilerTypeCommon, OutletTemperatureRange)
Nature of the ball to determine the loss coefficient default		String	
Thermostat Management type of the boiler		Int	
Coefficient of thermal loss	W/K	Double	
Total volume	L	Double	IfcBoiler + IfcPropertySingleValue (Pset_BoilerTypeCommon, WaterStorageCapacity)

The solution is either to add new property set to the IFC or to propose new elements for the IFC model to be added in the next version. This latter solution has many drawbacks: in fact, adding new elements in the model requires the development of new concepts, attributes and relations and this will take a considerable time. Also, the standard will contain much information becoming more complex. An alternative solution consists in the extension of the BIM model thanks to existing mechanisms in the data model such as user property sets. Actually, IfcPropertySet can be attached to any kind of elements with a key-value and thus enable the extension of their attributes. They are a special capability in the IFC Model allowing the extension of the model without requiring any changes to the standard itself. This solution surely offers more flexibility.

4.3 Discussion

IFC is developed to standardize information exchange in a building project. In our case, we tried to use it as a bridge format enabling the exchange of information between design tools and simulation tools. However, the data model features some limitations that hinder its effectiveness. In order to overcome its limitations, one possible solution is its enrichment using standard mechanisms (property sets). In our case, we focused on the IFC enrichment for HVAC system description with COMETH simulation engine. We followed the IDM process to structure this work in order to better define the needed elements and to draw the exchange requirements. As a result, we obtained a subset of the IFC model (a Model View Definition) representing a simulation view. This way, IFC files generated from CAD tools can be enriched with the specification of the HVAC systems before being transformed to the input format of the targeted simulation tool.

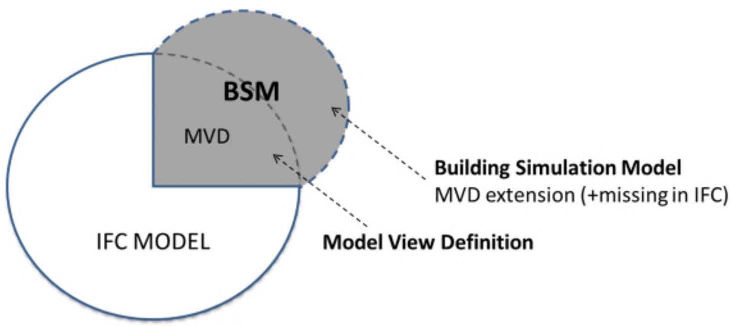

Figure 6 Building Simulation Model

We plan to benefit from the work performed in an ongoing European research project called HOLISTEEC, which is aimed at designing, developing, and demonstrating a BIM-based, collaborative building design software platform, featuring advanced design support for multi-criteria building optimization [31]. COMETH is the targeted simulation tool and one of the main assets of the project is a multi-physical simulation engine covering acoustics, environmental evaluation and lighting on top of energy.

Also, the BSM aims at being generic and at abstracting the notions and concepts needed for energy simulation, in order to decouple the energy simulation information from the actual energy simulation tool adopted. The abstraction provided by BSM will allow then to map the modelled concepts to a specific simulation engine input formats, such as COMETH or EnergyPlus, through a model-to-model transformation task.

An alternative, in order not to impact the IFC itself through the use of property sets, would be to store these additional parameters in an external file, and then to make a reference to it in the IFC – multi-modelling approaches [57] are clearly a sound basis to implement such approaches. To this end, one option is to resort to the link model approach [38], which is based on a separated model that acts as a bridge between the BIM model and the external data source. This model contains a set of link objects related to the relationships between different interdependent models; each link object is referenced with a number of model elements from these elementary models through their identifiers.

5 Conclusion

BIM interoperability and data exchange support are is still a research challenge. The emergence of standard BIM data formats, like the IFC, has brought many benefits but there remain many issues. The two main ones relate to the breadth and to the semantic depth of the building modelling languages. Even the most advanced and widely used building data exchange formats fail both to encompass the variety of concepts required to model buildings and, to fully disambiguate the information carried in the models. This is particularly true of BIM and simulation interoperability: to the best of our knowledge, no available tool enables for seamless and reliable generation of simulation model from BIM models.

This observation motivated the study lead in this paper. The aim was threefold: (i) to thoroughly review the BIM standards and, in particular, to highlight their limitations with respect to interoperability; (ii) to highlight the methods available to enhance BIM standards interoperability capabilities, with a focus on international standards; (iii) to assess the relevance of the IDM / MVD interoperability extension framework promoted by the BuildingSMART consortium through a dedicated use case, targeting the connection of IFC BIM with an energy simulation software.

The first lesson to draw is that there is a wide recognition of interoperability being one of the main enablers of future BIM solutions. The breadth and quality of the researches lead in this area are impressive. A second point is that the emergence of standard data exchange format (the IFC at first) has been much beneficial, but at the same time has left many issues unaddressed. While there was initially a general trend towards "all-in-one" standards, the current tendency favours extension and customization of available standards to fit with new requirements. The example of energy simulation is particularly illustrative. Embedding, in a single data exchange format, all energy simulation concepts, and all their variations along the simulation paradigms, tools, formats, etc, is simply not possible. The only relevant way to deal with the variety of applications that can be targeted from BIM is to provide adequate frameworks (methods and tools) for assisted customization of the data exchange formats. In this respect, the BuildingSMART consortium already set the scene with the delivery of major assets: the IFD (International Framework for Dictionaries), which allows for enhanced semantic definition; the MVD (Model View Definition), to specify and extract application-specific sets of information from the BIM; the IDM (Information Delivery Manual) to specify the mapping between the BIM and a third party format, and the related translation process. As shown in the paper, these components (that all relate to the IFC standards) are relevant and promising. In particular, they gave excellent results in the scope of a use case that we lead, which targeted the connection between IFC and a regulatory energy simulation engine.

However, several issues require further investigation. First of all, a future step can consist in the specification of a building simulation model allowing the mapping of IFC building description to different simulation environment, relying on multi-modelling approaches [38]. Then, one critical point is to provide more reliable and extensive software support for interoperability – e.g. to generate simulation models from BIM models. The BIM-based collaborative design environments developed in ongoing research projects like STREAMER [63] and HOLISTEEC [30], for instance, could be a relevant basis for such tools. One additional key point is to enable for backward interoperability. Where most of the ongoing works focus on downward connection, from BIM to third party tools and formats, it would be relevant to investigate ways to feed the modifications performed on the target model back to the BIM. In this respect, it would be particularly worth investigating dynamic interoperability approaches (e.g. based on linked data [39]]), to ensure real-time synchronization of BIM and target model.

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International Journal of Design Sciences and Technology
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Aims and scope

Today's design strongly seeks ways to change itself into a more competitive and innovative discipline taking advantage of the emerging advanced technologies as well as evolution of design research disciplines with their profound effects on emerging design theories, methods and techniques. A number of reform programmes have been initiated by national governments, research institutes, universities and design practices. Although the objectives of different reform programmes show many more differences than commonalities, they all agree that the adoption of advanced information, communication and knowledge technologies is a key enabler for achieving the long-term objectives of these programmes and thus providing the basis for a better, stronger and sustainable future for all design disciplines. The term sustainability - in its environmental usage - refers to the conservation of the natural environment and resources for future generations. The application of sustainability refers to approaches such as Green Design, Sustainable Architecture etc. The concept of sustainability in design has evolved over many years. In the early years, the focus was mainly on how to deal with the issue of increasingly scarce resources and on how to reduce the design impact on the natural environment. It is now recognized that "sustainable" or "green" approaches should take into account the so-called triple bottom line of economic viability, social responsibility and environmental impact. In other words: the sustainable solutions need to be socially equitable, economically viable and environmentally sound.

IJDST promotes the advancement of information and communication technology and effective application of advanced technologies for all design disciplines related to the built environment including but not limited to architecture, building design, civil engineering, urban planning and industrial design. Based on these objectives the journal challenges design researchers and design professionals from all over the world to submit papers on how the application of advanced technologies (theories, methods, experiments and techniques) can address the long-term ambitions of the design disciplines in order to enhance its competitive qualities and to provide solutions for the increasing demand from society for more sustainable design products. In addition, IJDST challenges authors to submit research papers on the subject of green design. In this context "green design" is regarded as the application of sustainability in design by means of the advanced technologies (theories, methods, experiments and techniques), which focuses on the research, education and practice of design which is capable of using resources efficiently and effectively. The main objective of this approach is to develop new products and services for corporations and their clients in order to reduce their energy consumption.

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