ABSTRACT
This paper discusses the current state-of-the-art in automated data exchange between Building Information Models (BIMs) based on the Industry Foundation Classes (IFCs) and energy simulation tools such as EnergyPlus. The paper discusses current IFC implementation in common BIM-authoring software, the difficulties in developing a building energy simulation model from design information initially created from an architectural perspective, and the benefits of standardizing the transformation of building geometry from an architectural view to the thermal view required for energy simulation. Additional data required for a complete energy simulation model and ongoing efforts to improve data exchange between BIM and energy simulation are discussed. A number of efforts related to improving the state-of-the-art are described.

INTRODUCTION
Automated data exchange between commonly used software tools for building design, construction, and operation has been a goal of the buildings industry for decades. One promising effort has been underway since 1994, organized by the International Alliance for Interoperability (IAI), now brand-named the buildingSMART Alliance and buildingSMART International (buildingSMART, 2011). buildingSMART has developed an open standard for data exchange between building industry software tools called the Industry Foundation Classes (IFCs). The IFCs provide software developers and users of Building Information Models (BIMs) a standard for sharing consistent, accurate building information amongst software tools used throughout a facility's life cycle.

While this goal has long been recognized as providing significant value in performing tasks such as energy performance analysis, the current state-of-the-art in software implementations supporting this process is woefully inadequate, particularly in the US market.

The lack of commercially available software robustly supporting this process is a result of industry culture and business case influences in addition to the technical shortcomings that are the focus of this paper. The US market for energy simulation services, despite recent growth due to drivers like the USGBC LEED, has not developed significantly beyond the use of standalone simulation tools by specialized practitioners more comfortable with manual building data input than automated data exchange. This has been historically a niche market lacking the revenue producing impetus for software vendor investment in new implementation. Furthermore, dominant vendors currently see a better business case for implementing embedded energy analysis tools within their flagship products rather than implementing robust data exchange with third-party tools that do not increase their revenue stream.

Thus, the effort to develop new data exchange utilities in the US has largely remained with the public sector, supported through activities by organizations such as the US General Services Administration (GSA), the US Department of Energy (DOE), the California Energy Commission (CEC), and others.

Alternative building information modeling efforts such as the Green Building XML (gbXML, 2011) have gained some traction with a more focused, more easily implemented data model. But even here many implementations fall short of reliably robust automated data exchange supporting rich energy simulation tasks across the building life cycle.

The technical challenges discussed in this paper are not therefore specific to IFC, nor for that matter are the cultural and business model barriers. Robust automated data exchange can be implemented using a variety of building information models.

This paper does not propose a solution to this situation. Rather, it attempts to identify the benefits of achieving the goal of automated data exchange, the requirements for achieving that goal, and several efforts currently underway to advance the state-of-the-art.

CURRENT PRACTICE
Building energy simulation has been practiced to date as a combination of science and art. There is a sound basis of science in the simulation algorithms, and in the level of building information detail required as input to these algorithms. The art of today’s practice comes into play in the current process of collecting building information from a variety of sources and
manually transforming this information into the specific input required by energy simulation software. While based on professional expertise, this process tends to be uniquely performed by each practitioner according to methods and rules-of-thumb developed over time by that individual. The result is a non-standardized process that produces energy simulation building models that can widely vary from one modeler to the next, even given the same initial building design information.

This non-standardized process has developed due to several factors including the traditional separation of architectural, energy simulation, and mechanical engineering professional disciplines and their participation in the current design process; a resulting dichotomy between an architectural view of a building and an energy simulation, or thermal view of the same building (Wilkins and Kiviniemi, 2008); and the standalone nature of software tools used by each of the participating design disciplines.

Under current common practice, a building is initially designed from an architectural perspective, producing a collection of building information defined from that perspective. An energy simulation specialist must then manually transform the architectural building information, and add missing required information to create the quite different Building Information Model (BIM) required for energy simulation (Bazjanac and Kiviniemi, 2007).

Automated data exchange offers substantial time savings, error reduction, and simulation model reproducability over this current practice.

**IFC TO ENERGYPLUS BUILDING INFORMATION TRANSFORMATION**

**Geometry**

The architectural view of a building design is generally created using a CAD tool selected by the architectural design team members. In this view, building floor plans are defined (drawn) according to functional space and individual room divisions. The floor of each building story is commonly a single slab spanning all spaces/rooms at that level. Building exterior elevations are defined as multi-story facades divided only by variations in orientation, façade construction type, and building elevation height. Exterior and interior architectural details are created with an eye to how they will render for client presentations.

This architectural view must be transformed into a very different view of the building for the purposes of energy simulation. Specifically related to geometry, the building surfaces (walls, floors, ceilings, openings) that tend to be monolithic in the architectural view must be subdivided into thermal boundary surfaces for input to energy simulation. This subdivision of building surfaces into boundary surfaces is an issue currently receiving attention in the buildingSMART community, and generally referred to in that context as the “space boundary” issue discussed in more detail below. This issue is further complicated by the mismatch between architectural spaces and energy simulation thermal zones.

The IFC data model contains a rich set of classes related to geometry representation, much of it built on existing ISO standards (buildingSMART, 2011). This rich modeling approach supports robust and flexible methods of representing building geometry, but at the same time allows variations in the implementation of IFC geometry export from different BIM-authoring tools.

The procedure within buildingSMART for formally documenting implementation standards for the IFCs is to create a Model View Definition for supporting a specific business process. An IFC Model View Definition (MVD), defines a subset of the IFC data model (schema) and a software requirement specification for implementing an IFC data interface supporting the target business process.

CAD vendors have been working together for several years to bring consistency to their implementations of IFC geometry export and import based on the IFC Extended Coordination View MVD (buildingSMART, 2011). However, these efforts have focused primarily on the exchange of an architectural view of building geometry between different BIM-authoring CAD tools, rather than exchanging detailed geometry with BIM analysis tools such as energy simulation. Wholesale exchange of building models between tools that view the building similarly is different from data exchange with so-called downstream analysis tools that view the building differently.

In particular, the process of subdividing monolithic architectural surfaces (e.g., multi-story façade walls and entire building story floor slabs) into space boundary surfaces is a difficult geometric operation that experience has shown to be much more reliably performed within the CAD tool being used to author the original building model rather than in a separate tool after the fact. A space boundary data object is already part of the IFC data model (IfcRelSpaceBoundary), but this part of the model has not been robustly implemented in current IFC import/export utilities for existing tools on the market. The buildingSMART and other industry groups are working toward this goal through the specification of additional MVDs that include space boundary data objects. Several of the leading CAD vendors have publicly committed to implementing IFC export of space boundary data, but require a comprehensive set of guidelines that would lead to consistent, certifiable implementation. See related work below for more details.

**Thermal Zoning**

Some of the currently available IFC-compliant CAD tools provide a mechanism for identifying thermal
zones within a building, at least as groups of spaces in the building model. This supports the potential to transform the architectural space/room view to an energy simulation thermal zone view.

Thermal zoning additionally requires appropriate treatment of intrazonal space boundary surfaces. At the least, the thermal mass of such surfaces should be accounted for. Where more detailed analyses are desired, such as daylighting or air flow, thermal zoning may need to be adjusted to properly account for the impacts of intrazonal surfaces.

Also, if the architectural view BIM includes functional space type identifiers for each space, thermal zone aggregations of internal loads and schedules must be accounted for.

Internal Loads and Schedules
The IFC schema includes properties for representing internal loads (occupancy, lighting, conditioning requirements) and a facility for representing schedules (IfcTimeSeries). These properties can be attached to individual space instances or associated with Space instances through a space type.

Alternatively, space type identifiers can be associated with space instances and used as an index into an external database of internal loads and schedules to be applied to thermal zones in an IFC to EnergyPlus transformation.

Construction and Material Thermal and Optical Properties
Most IFC to energy simulation transformation methods currently default construction and material thermal and optical properties of building elements. However, the need to default these properties is not a consequence of limitations in the IFC data model, which includes material related class definitions, but rather in the user interfaces of currently available IFC BIM-authoring tools that generally do not provide the means of inputting these properties, nor populating the exported IFC building model with them.

A simple approach to adding construction and material thermal and optical properties when transforming an IFC BIM to EnergyPlus is to default these properties based on crude interpretations of IFC building elements (e.g., exterior vs. interior walls and slabs). An incremental enhancement to this approach would be to use the IFC building element (wall, slab, window, etc.) description field, when available, as an index into a user selectable construction and material data library containing EnergyPlus IDF snippets for these objects. These data libraries could be based on standard data sets from sources such as ASHRAE 90.1 and California Title-24. This enhancement would also require sufficient information in the IFC building model to determine the correct order of material layers for a given space boundary surface needed to support reverse-ordering of opposite sides of the building element.

If BIM-authoring tools add support for construction and material property entry and export to IFC, the approach could be further enhanced to include these data in its transformation.

Shading Surfaces
Currently available IFC-compliant CAD tools do not create shading surfaces such as overhangs, fins, and lightshelves in a consistent manner that can be reliably detected in an IFC building model. This gap needs to be addressed in a robust transformation of building information for energy simulation.

HVAC Systems and Components
The flexible specification of HVAC systems and components in EnergyPlus presents a gap in IFC to EnergyPlus transformation that is difficult to fully overcome given the complexity of these systems. A relatively simple, but limited solution is to use the available EnergyPlus HVAC Templates when these suffice. To date, few IFC-compliant tools generate any detailed HVAC system or component information, which means there is nothing to transform into EnergyPlus from the IFC model anyway. See related work below for activities underway to correct this gap.

EnergyPlus Simulation Options
EnergyPlus provides a wealth of simulation options that require detailed input to specify including simulation control parameters (e.g., surface convection and heat balance algorithm options, equipment and system sizing options), daylighting analyses, dynamic fenestration controls, room air and airflow analysis models, economics calculations, and an overwhelming array of output requests. These features require domain expertise for input specification and output assessment that cannot be addressed in automated transformation processes and will not be addressed further in this paper.

RELATED WORK
A wide variety of activities have been undertaken over the past two decades to address the issues discussed above and improve software implementations based on accepted standards.

IFCtoIDF Transformation Utility
The IFCtoIDF utility for transforming building geometry in an IFC building model into an Input Data File (IDF) in EnergyPlus Input Data Dictionary (IDD) format was developed at the Lawrence Berkeley National Laboratory (LBNL) over a period from 1999 to 2004 with funding from the U.S. Department of Energy (USDOE).

The initial implementation of the IFCtoIDF utility imported an existing IFC data file, extracted instances of relevant IFC geometric representation objects from the IFC file, transformed these objects to EnergyPlus IDD objects, and created a rudimentary EnergyPlus IDF for the subject building.
(Hitchcock, 2000; Karola, et al., 2001). Since there is not a one-to-one correspondence between object classes in the IFC data model and the EnergyPlus IDD, the object data that are extracted from an IFC file must be mapped to their IDD counterparts. The geometric representation of objects also differs between IFC and the IDD, requiring a transformation between the two representations. This extraction and transformation process as implemented in the initial IFCtoIDF utility included the following IFC data objects: IfcProject, IfcSite, IfcBuilding, IfcBuildingStorey, IfcSpace, IfcWall, IfcWindow, IfcDoor, and IfcSlab. The resulting EnergyPlus v1.0 IDD objects that were written to the IDF included Building, Zone, Heat Transfer Surface (Wall, Floor, and Roof), and Heat Transfer Sub-Surface (Window and Door).

Only the geometry of these object instances was transformed and written to the IDF. Additional IDD object data, such as building simulation parameters and construction material characteristics, were defaulted and written to the IDF so that a preliminary EnergyPlus run could be executed. The principal output of this run was a DXF file that allowed a visual review of the transformed IFC geometry. Manual editing of the initially generated IDF could be performed to modify the default characteristics or to add missing elements like thermal zone internal loads and HVAC system descriptions. In the initial version of the utility, each instance of IfcSpace was mapped to a thermal zone in EnergyPlus since no IFC-compliant CAD tool at that time supported the existing IfcZone class definition, which would have allowed aggregation of spaces and partial spaces into appropriate thermal zones.

Previous software development experience related to implementing IFC interoperability had shown that an in-depth knowledge of the highly complex IFC object model is required to develop IFC-compliant software. It had proven quite difficult to read through the huge amount of building data stored in an IFC file and extract only that information needed by a particular application such as energy simulation.

To ease this type of development within the building services domain (e.g., mechanical, electrical, and energy simulation) Olof Granlund Oy, a building services firm in Finland, created a “middleware” development tool named BSPro (Building Services Pro) (Karola, et al., 2001). BSPro provides an application programming interface (API) enabling access to a subset of IFC classes for building geometry and thermal data properties without a deep understanding of the entire IFC standard. Using this middleware tool, a building services domain software developer can achieve IFC to EnergyPlus transformations with a much more reasonable amount of work.

For example, an instance of IfcWall, which might have been created as a curved surface spanning an entire exterior façade (i.e., the wall spans and bounds multiple IfcSpace instances), is simplified by BSPro methods that return only planar surfaces that bound a single IfcSpace.

The IFCtoIDF utility was developed as a Microsoft Windows® dynamic link library (DLL) that was a client to the BSPro COM-Server. A simple hosting graphical user interface (GUI) application was also developed that allowed an end user to specify the IFC data file to be read, and the EnergyPlus IDF to create. The IFCtoIDF utility was last modified in 2004 as part of a complex geometric modeling project that exposed limitations in each of the software tools employed at the time including Autodesk Revit, Graphisoft ArchiCAD, BSPro, the IFCtoIDF utility, and EnergyPlus.

The lessons learned from this work focused increased attention on the implementation of IFC export and import within existing tools at that time. In particular, the need to support additional elements of the IFC standard, primarily space boundary objects (IfcRelSpaceBoundary), was identified.

RIUSKA

Several years prior to the development of BSPro, Olof Granlund had developed RIUSKA, a graphical user interface for DOE2.1e for use by their design engineers. As part of Granlund’s adoption of IFC-based interoperability, BSPro was incorporated into RIUSKA to support automated import of IFC building model geometry into the RIUSKA environment (Karola, et al., 2001).

The success of IFC building model interoperability with RIUSKA is largely dependent on Granlund’s in-house expertise in using European-developed IFC BIM-authoring tools such as MagiCAD (MagiCAD, 2011) a building services design tool built on Autodesk platforms with additional support for IFC import and export. This success is in stark contrast to interoperability difficulties in the US market.

AECOO-1 Testbed

The Architecture, Engineering, Construction, Owner Operator, Phase 1 (AECOO-1) Testbed, jointly led by the buildingSMART alliance™ (bSa) and The Open Geospatial Consortium, Inc. (OGC, 2009), involved CAD BIM-authoring vendors, IFC data modeling experts, research laboratory scientists, and building design practitioners. The intent of this effort was to improve data exchanges during the building design phase supporting construction quantity take-off for cost estimation, and building performance energy analysis (BPEA).

The BPEA thread focused on defining and documenting data exchange requirements for early design energy analysis in Information Delivery Manual (IDM) and Model View Definition (MVD) documentation adhering to format guidelines developed by the buildingSMART Alliance; and incrementally enhancing IFC export/import...
capabilities in participants’ software tools to better support these requirements. These IDM and MVD documents form the basis for the BPEA portion of the GSA Concept Design BIM 2010 documentation (IFC Solutions Factory, 2009).

Participating BIM-authoring vendors were encouraged to enhance their IFC export capabilities to support the identified data exchange requirements in the BPEA IDM and MVD documents. IFC transformation utilities developed at LBNL, including the Geometry Simplification Tool (GST), IDF Generator, and IFC HVAC interface to EnergyPlus (Bazjanac, 2008 and Maile, et al., 2007) were employed to transform exported IFC data files for input to EnergyPlus.

A test case based on a partial GSA building model was used to coordinate project implementation efforts, and as an applied example in the culminating public webinar demonstration. Consequently, capabilities implemented in tools used in the demonstration were partially tailored to this particular building with limited resources available to generalize and test these capabilities over a wider range of example building models.

The issue of space boundary geometry was again emphasized as a major stumbling block to robust IFC BIM data exchange, which led to a continuing effort to specify implementation guidelines for this aspect of building models.

**Space Boundary Implementation Guideline**

As part of the AECOO-1 Testbed project, and building on work in a European open information environment research project InPro (InPro, 2010), a team was assembled to develop comprehensive specifications for IFC space boundary geometry implementation. As stated in an initial draft from this team, “This document provides guidance to software vendors looking to implement support (for) import and/or export of space boundaries for energy analysis in an IFC Building Information Model (BIM)” (Weise, et al., 2009).

Of note in this guideline is the concept of 1st- and 2nd-level space boundaries illustrated in Figure 1. The 3D walls of the architectural view of this simple three-space floor plan include the thickness of each wall. In creating an enclosed volume defined by boundary surfaces of each of the three spaces considered separately, planar surfaces must be created on the inner face of each wall with respect to each space, as shown on the top drawing in Figure 1. These planar surfaces represent 1st-level space boundaries for this floor plan. However, if the three spaces must be considered as individual thermal zones (e.g., controlled to different interior conditions or served by different HVAC systems), then further subdivision is required to create so-called 2nd-level boundary surfaces between the rectangular zone on the left and the two square zones on the right of the floor plan. Furthermore, to account for the thickness (but end) of the wall between the two square adjacent zones, an additional subdivision produces the tall, narrow surface bounding the rectangular zone, as illustrated in the drawing on the bottom. This leads to the necessity of further categorizing 2nd-level space boundaries for appropriate interpretation in transformation to energy simulation input.

![Figure 1 1st-level (top) and 2nd-level (bottom) space boundaries](image)

The purpose of the Implementation Guide is to clearly document rules for BIM-authoring export of space boundaries that can be reliably interpreted for consistent transformation between the architectural view and the thermal model view of buildings. The export and subsequent transformation must accurately account for significant impacts on energy simulation results, and must be robust enough to address not only the simple subdivision of surfaces in the Figure 1 example, but also in the highly complex geometries in actual building models. Actual building models include additional complicating elements such as window and door openings, curved surfaces, walls and slabs with empty openings (e.g., multi-story atria within open floor plans), embedded columns and beams, and shading surfaces.

**IFCtoEnergyPlus Utility and CEC BESM**

Two related projects using similar software code bases are currently underway, the NREL IFCtoEnergyPlus Utility project and the California Energy Commission (CEC) Building Energy Standards Modeler (BESM) Building Description Management project. Both projects seek to import building information models in common formats such as IFC and gbXML for transformation to energy analysis using EnergyPlus. These projects have initially focused on building geometry with the intent to extend transformation to additional data needs such as those discussed above.
These capabilities are being developed in the Microsoft Visual Studio 2008 environment using Visual C# 2008® and, for IFC import, use a significantly updated version of BSPro that is IFC space boundary aware. The utilities first import relevant IFC object instances into an internal building model, perform additional transformational processing, and then write out an EnergyPlus IDF. Functional tool versions of the underlying capabilities developed in these projects have not been released to the general public due to the continuing inconsistency in IFC space boundary implementation. Testing and enhancement continues.

**Curtain Wall for Energy Analysis MVD**

Another issue raised in the AECOO-1 Testbed was the transformation of curtain walls in building design plans, ensuring that incorporated glazing is properly accounted for when performing energy analysis. One continuing effort described elsewhere uses the MVD methodology to link user requirements for curtain walls into concepts which are implementable using the IFC model (Wong, 2011).

**ASHRAE RP-1468**

A research project funded by ASHRAE entitled “Development of a Reference Building Information Model (BIM) for Thermal Model Compliance Testing” is scheduled to be completed in 2011. The objective of this project is to “focus on the most common thermal features in today’s buildings that are assumed to have the greatest impact on a building’s energy use. The project will provide guidelines for describing thermal models extracted from a BIM and the rules for extracting the thermal model that are used in whole building energy analysis applications such as DOE-2, EnergyPlus, TRACE 700, and HAP.” The intent is that the product of this project would be BIM schema neutral, that is, it would not contain guidelines specific to the IFC data model. However, the project does have potential impact on industry promoted guidelines for architectural to thermal view transformation.

**ERDC-CERL LCM Program**

A long-term research program entitled Life-Cycle Model for Mission Ready, Sustainable Facilities is currently underway at the US Army Corps of Engineers (USACE) Construction Engineering Research Center (CERL). The overall program seeks to reduce life-cycle cost, increase mission readiness, and improve sustainability of built facilities, across their life cycles, through improved interoperability and collaborative business practices. The program is based on using IFC and the Construction Operation Building Information Exchange (COBie) to specify a life-cycle information exchange capable of supporting interoperability and collaboration from design through operations (USACE, 2011), and includes development of example BIMs for interdisciplinary testing.

**DISCUSSION**

A variety of efforts have been, and continue to be, undertaken to address the transformation of IFC architectural view building models to the thermal view required for energy analysis. The most comprehensive to date has been the AECOO-1 Testbed since it included not only IDM and MVD specifications, but also collaboratively developed implementer agreements that were implemented in software tools used in the final project demonstrations. However, the demonstration software tool implementations are not generally commercially or publicly available and supported.

It is not enough to specify processes and model view definitions on paper. It is not enough to document implementation guidelines for reference. It is not enough for individual BIM-authoring software vendors to implement their interpretation of these specifications. For example, while the IFC models generated by two different CAD tools used in the AECOO-1 project visually look the same, it was found that some concepts were implemented rather differently. In the absence of robust space boundary guidelines, one would expect variance in space boundary implementation by various BIM vendors. However, even with the best thought out guidelines, different native environments require interpretation during implementation.

There must ultimately be some form of certification to independently verify that implementations adhere to the specifications in a consistent manner, and that the resulting generated IFC models can reliably be interpreted for transformation. This certification process must deal with complex actual building designs as well as relatively simple test cases developed to explicate the implementation guidelines.

**CONCLUSION**

We have discussed limitations that we have observed in efforts to date to bridge the information gap for transforming IFC building information models to support energy analysis.

The principal obstacle remains robust transformation of thermal view space boundary geometry. Advances have been made in the specification of information delivery manuals (IDM) and model view definitions (MVD) for this use case, and an implementation guide for space boundaries has been drafted. However, there has not been consistent implementation of this MVD in BIM-authoring tools. Lastly, no commonly accepted robust certification method to test and diagnose existing and future implementations have been developed.

Automated data exchange between commonly used software tools for building design and energy analysis remains an elusive goal.
REFERENCES


