Model based cost and energy performance estimation during schematic design

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ABSTRACT: The U.S. General Services Administration (GSA) may require the submission of an IFC based Building Information Model (BIM) at the end of schematic design in the foreseeable future. The driving force behind this possible requirement is GSA need to obtain much more frequent and reliable cost and energy performance estimates from building design projects they fund. This, and similar initiatives that may be forthcoming in the U.S. and elsewhere, will force architectural and engineering firms to use model based CAD software in their work. Cost estimating and building energy performance simulation and analysis, done with interoperable software tools, will draw some of the data needed for its work directly from a BIM.

Direct import and reuse of building data will inevitably cause process change in practice. Some design decisions will have to be made (much) earlier in the design process; greater emphasis will have to be given to multi-disciplinary work earlier in a project. A need for new skills will arise in practice. A "new generation" of software tools will be deployed and project staffs will have to learn how to use them competently and effectively.

This paper describes the process of data import from an IFC compatible BIM for cost and energy performance estimating, and what is possible with currently available software. It discusses anticipated effects on architectural and engineering practice in North America, and action to be undertaken to make the use of IFC compatible building information modeling with "downstream" applications a reality.

1 INTRODUCTION

In a memorandum to PBS Assistant Regional Administrators dated December 23, 2003 (Moravec 2003), the Commissioner of the U.S. General Services Administration (GSA) instructed them to "Prepare Design Deliverables and As-Builts using Standardized IFC based Building Information Models: Cost overruns and claims can be reduced on our construction contracts by improving the quality of our design product. New technology now affords us the opportunity for quantum improvement in design quality by building our buildings virtually before building them physically. … This technology is now available to the construction industry in the form of interoperable building information modeling using Industry Foundation Classes (IFC). Interoperable object model technology also allows automated standards checking and cost estimating to better control project scope and cost. ... The goal will be to provide IFC based building information models in support of all national office concept reviews on projects receiving design funding in FY 2006 and beyond." The memorandum also states the Commissioner's concern with sustainability of GSA buildings and directs the "… implementation of specific OCA design initiatives [such as] LEED certification, …" The memorandum establishes the goal of using IFC based building information models in GSA project reviews and the objectives of automated standards checking, cost estimating and LEED rating.

Early assessment of LEED rating level classification the building design may achieve is meaningless without considering the evaluation of the designed building's energy performance (LEED 2005). For LEED classification purposes that evaluation is based on "whole building" annual energy performance simulation. HVAC equipment and systems designed for the building are a vital component of the simulation, and account for a significant portion of the building cost (usually around 20% or more). Early assessment of LEED rating potential and calculation of more accurate early cost estimates require the use of building energy performance simulation at the same early stage of building design.

Different individuals and groups interpret Building Information Modeling differently (Laiserin 2002). The definitions are continuously evolving and it appears that every newly formed group with

interest in interoperability coins its own definition. A Building Information Model (BIM), the *noun*, is defined here as an *instance of a populated data model of buildings* that contains multi-disciplinary data specific to a particular building which they describe unambiguously. It is a *static* representation of that building (i.e. it uniquely defines that building in a section of time) – it contains "raw" data that define the building from the point of view of more than one discipline (Bazjanac 2004).

It is impossible to store *all* data related to a building in a BIM. The shear volume of data related to a building would render such a BIM impossible to manage, navigate, query and share; such a BIM would be useless. The IFC data model was designed to contain only the fundamental static data from which other data can be derived. Derived and time based data are stored externally – a BIM contains only references and/or links to locations where such data are stored.

Even so, the IFC data model defines many more data types and formats than any single software would need or could create. Consequently, a fully populated IFC based BIM contains much more information than any cost or energy estimating software needs to exchange or make use of. Data sets which are pertinent and are subject to exchange among software applications that serve a particular industry discipline or service a specific set of tasks are defined in specific "views" of the IFC model. Current "views" of the IFC data model include the architecture and coordination "views" (these mostly define data types and formats that populate a BIM with building geometry and geometry related data), the quantity take-off "view" (that defines data types and formats for cost estimating), and the thermal "view" (that defines *passive* performance data types and formats for energy performance estimating). IFC compatible software typically represents a particular "view" of the IFC data model; its IFC interface maps to the software's own data structure only those IFC data type and format definitions that are identified in the particular "view" and *ignores* all other.

Creating a BIM makes sense only if software is available to populate the BIM with data that can be reused by other software, and only if software exists to extract and import data from a BIM. Thus the primary purpose of BIM is to facilitate reuse of reusable data.

This paper discusses typical tasks encountered in the process of generating early cost and energy performance estimates. It defines types of software interoperability and identifies directly and indirectly IFC compatible (interoperable) software currently available in North America. It identifies and groups software per task – BIM authoring, cost and energy performance estimating. It also identifies "target" software that, as a group, can perform all tasks necessary to generate cost and energy performance estimates.

The paper also reviews data types that must be populated in a project BIM. These are data types that are required for successful deployment of cost and energy performance estimating software in schematic design. It then assesses the availability of such data and identifies data types that are exchanged among "target" software and thus should be contained in the BIM. Some data types that are necessary cannot be exchanged and are thus kept in external data bases.

Interoperability and IFC compatibility assessments are limited to those relative to the IFC2x2 version of the data model, as this is the only version of IFC that supports *all* data types that are subject to exchanges among "target" software. Interoperability and IFC compatibility based on IFC2x and prior versions of the data model are noted as appropriate. All software assessment is based on software versions, their characteristics, functionality and status as of March 31, 2005. Software not usable in schematic design, proprietary software used in schematic design but not on the market, software that "will be released soon" and software that is "just about to be released" is not considered here. Software targeted for foreign language markets (such as Japanese and French) and not available in North America is not considered either.

2 SOFTWARE AND SOFTWARE ISSUES

Surveys of AEC industry software on the market today (see *2.2 CAD BIM authoring software* below) show that only *one* BIM authoring tool is currently capable of populating a BIM with *all* building geometry definitions that are necessary to operate other tools engaged in the delivery of automated or semi-automated cost and building energy performance estimates. The same vendor provides an integrated cost estimating tool which is the only cost estimating software in North America that can make use of *all* necessary information contained in an adequately populated IFC based BIM. Surveys of AEC industry software also show that only *one* energy performance simulation tool on the market today (see *2.6 Energy performance simulation and analysis software* below) is IFC compatible, capable of importing building geometry needed for the simulation from an IFC based BIM, and capable of adding HVAC equipment and systems definitions and schedules to an IFC based BIM.

While several software tools (often employing own proprietary data models of buildings) may be individually able to perform single tasks in the process of populating a BIM and generating cost and energy performance estimates, as of this writing the actual choice is limited to only a few tools that are IFC

compatible. In order to create a valid, fully populated IFC based BIM and IFC based cost estimate, one *currently* has to use a single vendor's integrated BIM authoring and cost estimating tool, and the single publicly available building energy performance simulation tool (in addition to any indirectly interoperable tool of choice – see below). This applies to every project, regardless of what BIM authoring tool(s) the design team may be using natively. As other vendors' tools, including other cost and energy performance estimating tools, become directly IFC compatible, the choice of usable tools will increase.

2.1 *Software compatibility with IFC*

An IFC based BIM is essentially a data base for a given building with data formats and internal organization that follow the rules defined in the IFC data model of buildings. If these rules are the rules defined in IFC2x2, the BIM is IFC2x2 based. An IFC based BIM has a form of an IFC file. If the exchange of information in that file is accomplished by "physical file" exchange, software engaged in the exchange must be compatible with the particular version of IFC in which the BIM was created. Otherwise it cannot import the IFC file or write to it. If a BIM is resident on an IFC model server and is accessed via web services, the IFC version is irrelevant as long as there is no data format incompatibility among the IFC versions in question.

Software compatibility with IFC is obtained with a mapping interface between the software's internal data model and the IFC data model that translates the relevant IFC definitions into software's own data model formats and/or translates the relevant software's data model definitions into IFC format. Software that has an IFC2x2 interface is *directly* IFC2x2 compatible (Figure 1). Software that does not have such an interface and cannot perform the necessary data translations is not IFC2x2 compatible, is *not directly interoperable* with IFC2x2 compatible software, and cannot be used to *directly* write data from/to an IFC based BIM.
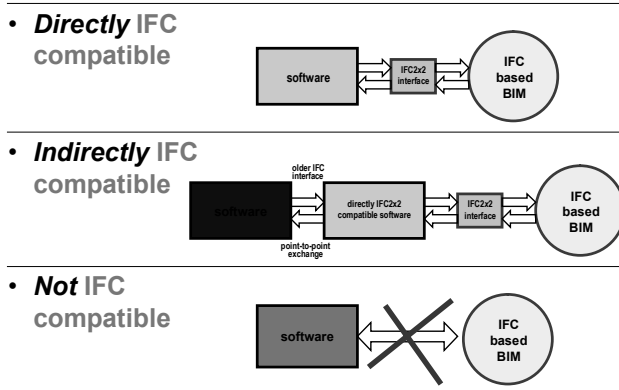

Figure 1. Types of software compatibility with IFC

Some IFC interfaces are based on older versions of the IFC model (prior to IFC2x2, such as IFC2x or IFC 2.0) and can populate a BIM only partially: They can populate a BIM only with information that was exchangeable and definable on the basis of the particular version of IFC. Software with such interfaces is *indirectly* IFC2x2 compatible – used as necessary *in conjunction* with directly compatible software it can participate in adequate population of a BIM. If data exchange with a BIM is of the "physical file" kind, the BIM can be populated with data from indirectly compatible software only through an "intermediary:" directly compatible software that also has an IFC interface in the version of the particular indirectly compatible software's IFC interface (Fig. 2). In that case the directly compatible software can read the file submitted by the indirectly compatible software, resave it in IFC2x2 format and populate the BIM. Directly compatible software can also extract the data from a BIM and then write it in IFC format that is readable by indirectly compatible software.
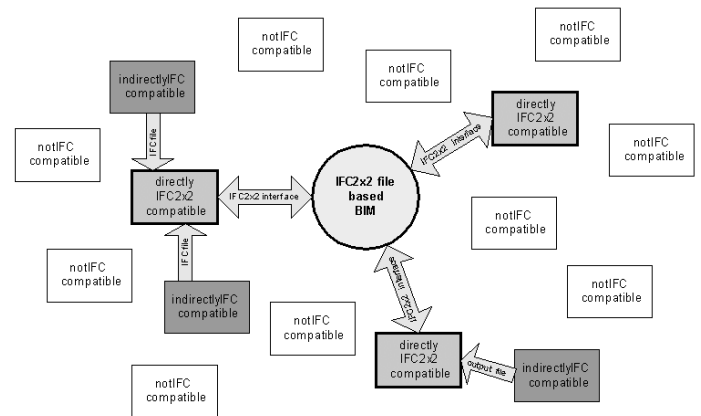

Figure 2. Path from indirectly IFC compatible software to an IFC2x2 based BIM via "physical file" exchange

Some software has no IFC interface whatsoever, but has an export data format or utility that allows it to export its building model data to directly IFC compatible software; the IFC compatible software can then populate a BIM with data originally defined by such fundamentally IFC incompatible software – such software can thus be used as *indirectly* interoperable software to provide data for a BIM.

If a BIM is resident on an IFC file server, indirectly compatible software may be able to access it directly (Figure 3). In that case such software may be able to import data from and write it to a BIM itself, without the need for "intermediary" software.

Published lists and reviews of software that is currently used in building design, construction and operations abound. Some of the lists and reviews specifically identify BIM authoring software, or software that is used in cost or energy performance estimating. These include software reviews and analyses published monthly in Cadence (a widely distributed AEC industry CAD magazine), reviews in LaiserinLetters (Laiserin 2005), the Newforma White Paper (Howell and Batcheler 2005), the Geo-

praxis Green Building Studio web survey of AEC design practice (Geopraxis 2004), a list of minor special purpose cost estimating software (OzGrid 2004), the Building Energy Software Tools Directory from the U.S. Department of Energy (U.S. DOE 2005), the BEST list from the University of Hong Kong (Hui 2005), an informal survey of IAI users by the IAI Technical Advisory Group (TAG 2003), and more. A review of these sources identifies software that is or can be used early in the building design process and specifically in schematic design.
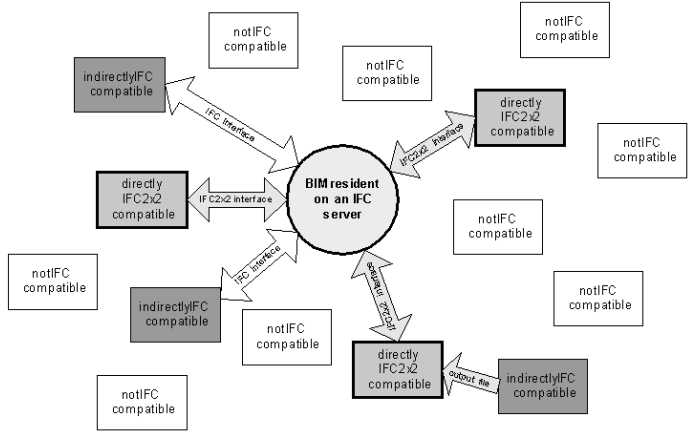

Figure 3. Path from indirectly IFC compatible software to an IFC2x2 based BIM residing on an IFC server

2.2 CAD BIM authoring software

The only *directly* IFC2x2 compatible BIM authoring tool on the market *today* is ArchiCAD 9 from Graphisoft. It is a sophisticated CAD tool designed to primarily serve the architectural design community. Compatibility with the IFC2x2 data model is achieved via ArchiCAD's IFC2x2 Utility. Besides IFC2x2 files, ArchiCAD 9 can read and write files in IFC formats that preceded IFC2x2, such as IFC 2.0 and IFC2x.

A number of BIM authoring tools have interfaces to previous versions of the IFC data model. The Geopraxis' web survey (Geopraxis 2004) shows that such tools most frequently used in North America are Architectural Desktop (ADT) 2005 from Autodesk and Microstation Triforma from Bentley, with some market presence by Allplan from Nemetschek. None of these tools are currently IFC2x2 compatible. To populate an IFC2x2 based BIM with these tools one must first import the IFC file generated by such a tool into ArchiCAD 9, then save it in IFC2x2 format. This makes these tools *indirectly* IFC2x2 compatible (Figure 1).

SketchUp from @Last Software is a different kind of *indirectly* interoperable tool. SketchUp has no IFC interface whatsoever, but generates output files that can be imported via a third party plug-in into ArchiCAD 8.1, resaved as ArchiCAD files and moved into ArchiCAD 9 for saving in IFC2x2 format. In that way one can populate an IFC based

BIM with building geometry data that was originally created with SketchUp.

Visio 2002 Professional from Microsoft is yet another *indirectly* interoperable tool that has only an IFC 2.0 interface. The tool has limited functionality: It can only model building designs for which the third dimension can be *completely* extruded vertically from 2-D floor plans. One can import an IFC 2.0 file generated by Visio into ArchiCAD 9, add to it or modify it if necessary, save it in IFC2x2 format, and populate an IFC based BIM with data some of which were originally generated with Visio.

Most of the other "3-D" CAD tools on the market today do not even qualify as BIM authoring software – they create 3-D definitions of surfaces (mostly for visualization of some kind) but do not associate any other buildings related information with them. If their internal architecture is object oriented, their objectivity is mostly limited to drafting; their objects do not carry any kind of "buildings" intelligence. Obviously, none of them can be IFC compatible.

A notable exception among previously *non IFC compatible* CAD tools is Revit 8 from Autodesk. This is a true BIM authoring CAD tool, even if the BIM it populates is based on a proprietary building data model, not IFC. The recently released Revit 8 includes an IFC2x2 "*export only*" interface that could not be properly tested on non-trivial buildings at the time of this writing (because one cannot import such test files with the current interface). With a properly working interface one will be able to populate an IFC based BIM with data generated in Revit 8. This will make Revit 8 a directly IFC compatible CAD BIM authoring tool.

2.3 BIM checking and verification

Solibri Model Checker (SMC) from Solibri can "spell check" an IFC based BIM to find and report inconsistent and conflicting, as well as required but missing definitions in a BIM. Different types of checks are defined as "constraint sets." These can perform a variety of standard BIM checks that include checks for typical modeling problems, for inconsistent component properties and profiles, for different kinds of component interference, and more. SMC provides exceptional "see through" visualization that makes it very easy to locate a reported problem in the building model. Solibri also distributes the Constraint Set Manager (CSM) which allows end users to write custom constraint sets that are then executed by the Model Checker. SMC is *directly* IFC2x2 compatible and can read and check any BIM that is based on any version of the IFC data model. It is the *only* tool in the category of model checking software on the market today.

2.4 Cost estimating software

While most cost estimating tools can perform quantity take-off or import quantity take-off data, all cost estimating software requires the use of associated and/or additional data bases that contain unit costs and other industry data needed to prepare an estimate. Data in such data bases often require regional or localized adjustments; cost estimating can seldom be fully automated when initially used in a project.

No standalone cost estimating software available in North America today is *directly* IFC2*x*2 compatible. IFC compatible software, such as ToCoMan from TocoSoft (a Finnish vendor) or CI Estimator from CRC (an Australian vendor), need adaptation to North American construction practices, prevalent classifications systems, manufacturer data, unit system and more before they can be widely used in North America.

Constructor and Estimator from Graphisoft are a special case of interoperable cost estimating software. They are two of several Graphisoft tools that use the Graphisoft "virtual building" model as the building data model and repository of information; ArchiCAD 9 is an integral part of that group of tools. Constructor and Estimator are linked directly and operate as a fully integrated pair. Constructor uses ArchiCAD 9 as its user interface and to supply and/or modify building geometry, and is fully integrated with it. Since ArchiCAD 9 is a *directly* IFC2*x*2 compatible tool, Constructor inherits all interoperability features from it and can itself be considered *directly* IFC2*x*2 compatible.

Graphisoft's Estimator in itself is not IFC compatible, but since it is integrated with Constructor (and thus also with ArchiCAD 9) it can use data contained in an IFC based BIM. The data flow from an IFC based BIM is one-directional, however: Graphisoft's IFC2*x*2 Utility cannot at present write original data generated by Constructor or Estimator to an IFC file. Thus Constructor and Estimator cannot populate an IFC based BIM themselves.

PrecisionEstimating from Timberline is *indirectly* IFC compatible, though the indirect compatibility in this case is "reverse:" It has an IFC 2.0 interface that allows it only to import building geometry from an IFC 2.0 file. This requires intermittent use of a separate directly IFC2*x*2 compatible tool that can extract data from an IFC2*x*2 based BIM and save them in IFC 2.0 format for reading by the Timberline IFC 2.0 interface. PrecisionEstimating contains several integrated modules, including CAD Integrator that manipulates building geometry.

The North American AEC industry uses a variety of other cost estimating tools, such as WinEst, US Cost, CPR, and more. Not one of these tools has an IFC interface of any kind and thus none are IFC compatible.

2.5 Thermal zoning and space boundary definition

The simulation and analysis of a building's energy performance are based on the building's thermodynamic behavior and require a "thermal" view of the building. "Thermal" view is quite different from "architectural:" Individual architectural spaces (or rooms) that have the same thermal behavior are agglomerated into thermal zones. This agglomeration is a necessary step in the modeling of energy performance of any building. Performed manually, it amounts to redrawing the building, which is very laborious and resource consuming, and is a major deterrent to automating the simulation and analysis of building energy performance. ArchiCAD's IFC2*x*2 Utility allows one to create new IFC zones in the building model's "object tree" and drag-and-drop appropriate spaces/rooms found in the tree into the newly created IFC zones. This facility saves many hours of labor and eliminates possible drawing mistakes.

State of the art building energy performance simulation and analysis software also require proper definition of thermal "space boundaries" in the input of building geometry. Figure 4 visually explains issues related to "space boundaries." A construction like a wall or a slab is defined in CAD BIM authoring software as a single instance in its full length (long wall in the left image in Figure 4). That construction has two sides, each of which may be shared by more than a single space or zone. To properly account for thermal transmission through the construction, the originally single construction must be segmented into areas that uniquely belong to each space or zone. The segmentation will increase further if the unique construction segments do no coincide on both sides of the construction. In the example in Figure 4 four zones share the same wall (two on each side of the wall). Proper allocation of "space boundaries" divides this wall into three segments (right image in Figure 4): one wall segment is uniquely shared by zones 1 and 3, another segment by zones 2 and 3, and yet another by zones 2 and 4. Any definition of building geometry for energy performance simulation and analysis software must include resolved "space boundaries."
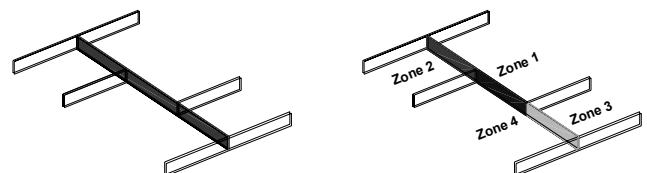

Figure 4. Definition of "space boundaries" for thermal modeling

Manual definition of space boundaries for non-trivia building designs is very tedious, resource consuming and error prone. To be useful, any automated or semi-automated generation of energy performance

estimates must employ software that generates proper space boundaries *automatically*.

ArchiCAD 9, via its IFC2*x*2 Utility, is currently the only BIM authoring software on the market that can properly accomplish this task. This, and the currently unique facility to drag-and-drop space objects into IFC zones, makes ArchiCAD 9 a currently necessary and unavoidable element in automating the estimation of building energy performance. It explains why it is necessary to import building geometry from an IFC based BIM and "re-work" it with the ArchiCAD IFC2x2 Utility before loading it into energy performance estimating software when the BIM was populated by another CAD BIM authoring software.

2.6 *Energy performance simulation and analysis software*

Building geometry, as defined with CAD BIM authoring software, is full of detail that "downstream" software does not necessarily need. A BIM must contain such "rich" definition of geometry because some "views" of the model and related software (including cost estimating) need it. Models of building geometry employed by most energy performance estimating tools are fairly simple: They define only the length, height, width, and location of *planar* surfaces relative to a coordinate system. Any additional geometry data contained in a BIM are redundant to such tools. Thus geometry contained in a BIM has to be simplified for use in energy performance estimation, a task suited for middleware.

EnergyPlus from the U.S. Department of Energy (DOE), a tool in the public domain, is the only building energy performance simulation and analysis software that is *directly* IFC2*x*2 compatible. It is a "state of the art" energy simulation tool designed to simulate energy performance of buildings of any type and complexity, in any location, for any period of time. The tool uses BS Pro COM Server middleware from Olof Granlund OY (a Finnish vendor) and its EnergyPlus client from LBNL (IFCtoIDF) to simplify building geometry imported from an IFC based BIM. While BS Pro can currently write six specific parameter values to an IFC file, neither BS Pro nor IFCtoIDF can export new data to a BIM. However, EnergyPlus has an IFC HVAC interface from LBNL that makes it possible to import HVAC definitions and building use schedules from a BIM and/or populate a BIM with the same.

EnergyPlus cannot write *results* of simulation and analysis to a BIM *by design*. Each energy performance simulation generates enormous volumes of data – a project BIM could not possibly contain all those data and still be navigable, searchable, and generally manageable and useful. Instead, SMIET (another interoperable tool from LBNL) places references and/or links to external files that contain the results of simulation and analysis, or contain all simulation input data necessary to recreate the simulation and analysis into IFC2*x*2 based BIMs. SMIET – a *directly* IFC2*x*2 compatible BIM authoring tool for HVAC equipment and systems definition – can extract from and/or populate an IFC2*x*2 based BIM specific data related to energy simulation that are not an integral part of EnergyPlus simulation and thus cannot be imported or exported with the IFC HVAC interface for EnergyPlus. Such data include manufacturers' product information, maintenance information that is not time based, and more.

Surveys show that a substantial portion of building energy performance simulation and analysis in North America is still done with DOE-2 (a predecessor of EnergyPlus) and its various commercial or public domain derivatives. None of these has an IFC interface of any kind. However, DOE-2.1E and DOE-2.2 input can be at least partially translated into EnergyPlus format with an EnergyPlus utility. This makes DOE-2 and all of its derivatives a special case of *indirectly* IFC2*x*2 compatible software, similar to SketchUp (see above).

Other currently available energy performance estimation tools do not have an IFC interface of any kind and are thus not IFC compatible. These include TRNSYS, HVAC Solution 3.0, and others from North America, and ESP-r and TAS (two tools from U.K. with some presence in North America). Some of these tools can import (simplified) building geometry from CAD files generated by directly or indirectly IFC compatible software, (such as gbXML, which imports building geometry and includes it in the input it creates for DOE-2 or EnergyPlus), but none can export information back to BIM even through an "intermediary."

2.7 *HVAC design software*

Unlike energy performance estimation software discussed above (with which it has many common aspects), HVAC design software is used specifically to design HVAC systems that serve a building. Surveys show that such software is used by virtually all HVAC designers; it is not coincidental that the two most prominent design tools of this type come from HVAC manufacturers (Trace from Trane, HAP from Carrier).

Unfortunately, none of the HVAC design tools used in North America, such as Trace, HAP or the Right-Suite Commercial suite from Wrightsoft, are directly or indirectly IFC compatible. None have an IFC interface or any ability to have data they generate added seamlessly to a BIM. A couple of European tools are either directly (such as DDS from Norway) or indirectly IFC compatible (such as MagiCAD from Finland). Both are primarily ducting and piping design tools, and neither has a presence on the North American market yet.

The lack of interoperable HVAC design software poses a serious issue in BIM authoring. EnergyPlus (not a primarily HVAC *design* tool) provides the only way to populate a BIM with HVAC data; to do that one has to enter data describing HVAC equipment and systems, possibly already defined by an HVAC design tool, manually into EnergyPlus before those data can be placed into a BIM via the IFC HVAC interface to EnergyPlus.

3   DATA AND DATA TYPES

Software manipulates data. For software to run and generate results, its user must "input" data. Interoperable software obtains some of the data it manipulates seamlessly (i.e. automatically or semi-automatically) from other interoperable software or data bases. Other parts of input data sets it manipulates come from external sources (i.e. from software or data bases that are not interoperable, or from information available to the end user that is not in electronic format) and are entered by the end user. Some data are yet generated by the software itself.

If a particular (required) datum is not found in a BIM, interoperable software is still useable. It merely means that this particular datum is provided from another source. That in fact is how all interoperable "downstream" software operates today. Interoperable cost and energy performance estimation software draws building geometry and some other data from a BIM. The rest of the data input content is completed with data from data bases contained in computer files (such as those that contain task libraries and/or input data for previous projects), manuals and catalogues (such as those that contain manufacturers' product and/or performance data) and information that comes from end user's training, knowledge and experience. If the end user provides input information that links the software to external electronic data bases (as is the case for weather data in energy performance estimation), the software automatically fetches the needed data. Otherwise, the remaining data are entered by "copy-and-paste" or manually.

Most sophisticated "downstream" software has a mechanism to protect it from missing data that are mandatory for its operation.

Table 1. Data types created in schematic design and used by cost and energy performance estimation software

Discipline	Data types that define	IFC2x2 BIM authoring tool(s)	Determined in schematic design	Data source(s) for software
Architecture	Building geometry	IFC compatible CAD software	Sufficient	BIM
	Construction materials	None adequate	Preliminary	External data base
	Manufacturers' components	None adequate	Preliminary	External data base
Structural engineering	Frame	Geometry: IFC compatible CAD	Preliminary	BIM, experts
	Load bearing walls	Geometry: IFC compatible CAD	Preliminary	BIM, experts
	Columns	Geometry: IFC compatible CAD	Preliminary	BIM, experts
	Beams	Geometry: IFC compatible CAD	Preliminary	BIM, experts
	Slabs	Geometry: IFC compatible CAD	Preliminary	BIM, experts
	Foundations	Geometry: IFC compatible CAD	Insufficient detail	Experts
MEP	HVAC equipment & systems	EnergyPlus	Preliminary	EnergyPlus input
	Ducts & pipes	None (in North America)	Insufficient detail	Experts
	Electrical equipment & systems	None (in North America)	Preliminary	Experts
	Wiring	None	Preliminary	Experts
	Fire safety equipment & systems	None	Insufficient detail	Experts
	Lighting equipment & systems	Geometry: IFC compatible CAD	Preliminary	BIM, experts
	Utility rates & schedules	None	Sufficient	Local utility
Civil engineering	Excavation	None	Insufficient detail	Experts
	Hauling	None	Insufficient detail	Experts
	Grading	None	Insufficient detail	Experts
	Drainage	None	Insufficient detail	Experts
	Irrigation	None	Insufficient detail	Experts
Landscape architecture	Landscaping	None	Insufficient detail	Experts
	Planting	None	Insufficient detail	Experts
Construction management	Methods	None	Preliminary	Experts
	Resources	None	Preliminary	Experts
Building operations	Occupancy schedules	EnergyPlus	Sufficient	EnergyPlus input
	Internal loads schedules	EnergyPlus	Preliminary	EnergyPlus input
	HVAC systems schedules	EnergyPlus	Preliminary	EnergyPlus input
	Plant schedules	EnergyPlus	Preliminary	EnergyPlus input

Some software has "default" values for such data types built into its code; if the input data set fails to include a particular required datum, the software uses the default value for it. (End users have to be aware of that default value to fully understand the results the software generates.) Other software interactively reminds the end user to input the datum and may not proceed until a value is entered.

The list of needed and used data types also depends on project type. Software supporting the design of a new building may need a full set of data it can manipulate. Even so, at a particular stage of a project design decisions may emphasize a particular set of issues related to a discipline (e.g. the building structure), leaving other issues (e.g. building envelope or electrical systems) for future consideration. In that case software will use only data related to the particular area of emphasis (i.e. structural design). In renovation projects (such as HVAC equipment and systems upgrade) some areas of the building may never be considered (e.g. foundation design) and "downstream" software (such as cost estimating) will not receive any data pertinent to those area, will not include them in its work and will not calculate any results pertinent to them.

Input sets provided by end users also vary depending on what information is available to end users at the time, and end users' knowledge, experience and skill in the use of the particular software. Everything else being the same, two users are not likely to prepare identical input data sets; yet both are likely to obtain valid results from the software, at least in their own minds.

3.1 *Data types manipulated by cost and energy performance estimation software*

Table 1 shows data types that are used in cost and energy performance estimating. It also shows types of IFC compatible software that can populate a BIM with (some of) those data, and sources of data used in the operation of "target" software. Data types in the table are organized by industry discipline that is expected to participate in or provide information to design decision making during schematic design. Within industry discipline, data types are organized by building component type.

In absence of a tool capable of placing data of a particular type in a BIM, such data must be supplied to the software from external sources. In some cases BIM authoring tools can populate a BIM with only a segment of data used by "target" software; in that case the remaining data are also provided to the software from external sources. "External sources" may include electronic or printed data bases, product catalogues and manuals, previously defined relevant data (defined for other projects), or information selected or supplied by experts. Information from experts may result from experts' knowledge of the particular project, subject and/or software, from experience in the use of software in similar projects, and/or experts' specialized training.

Design decisions in schematic design result in data for software that are defined at different levels of detail and confidence. Some data types can be defined sufficiently. Other data are typically defined only in preliminary form: Definitions may be incomplete, may not contain much detail, and/or may change as design progresses. Yet other data are defined in form insufficient to use with "target" software, or are not defined at all.

Some of the data types are defined insufficiently or not at all because those who are expected to define them do not participate in schematic design for the particular project (they typically join the project and contribute their data later). To improve the accuracy and quality of cost estimates during and at the end of schematic design, the project team should include members from the top six (of seven) disciplines listed in Table 1 and should *start work of these disciplines already during schematic design*. To improve the accuracy and quality of energy performance estimates, MEP work during schematic design should include specific building systems designs and sufficient knowledge of building operations for the building that is being designed.

The absence of sufficiently defined data does not necessarily prevent the use of "target" software. Discipline experts and/or software use experts can reform data or supply data that are meaningful for the project and enable "target" software to operate and produce sought results. *That is how industry software is used in most cases today.*

3.2 *Minimum data sets*

From a technical point of view, the definition of a "BIM minimum data set" primarily depends on the software that uses data extracted from a BIM in its operation. Currently, "minimum" data sets for cost and energy performance estimating "views" should include all data types (a) that are used by the single vendors' cost and energy performance estimating tools discussed above, (b) that are also defined in the IFC2*x*2 data model, and (c) that can actually be populated with project information. Data used by these tools are explicitly defined in the Input section of each respective Users Manual. The respective tools' IFC interfaces determine what data can be populated and exchanged. From a practical point of view, minimally "required" data sets should be determined individually for each project on the basis what data are required to obtain the sought results.
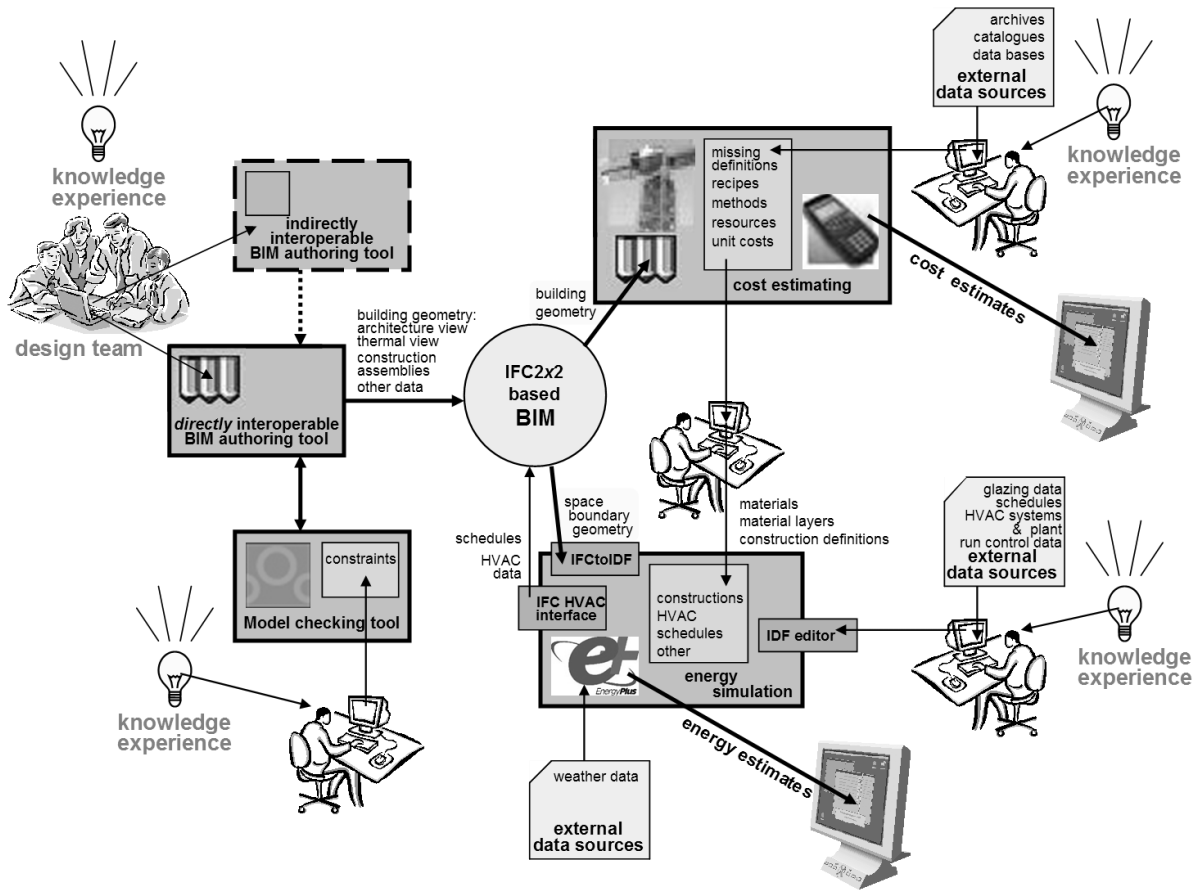
Figure 5. Data generation and flow in current cost and energy performance estimating

4 GENERATION OF ESTIMATES WITH DATA FROM AN IFC BASED BIM

The process of generating an IFC based BIM and cost and energy performance estimates using data from that BIM, as possible today, is diagrammed in Figure 5. The design team defines the building geometry and composite construction types in ArchiCAD or in an indirectly interoperable CAD BIM authoring tool, such as ADT, Microstation Triforma or other software (see the discussion of indirectly interoperable software in *2.2 CAD BIM authoring software* above). If the former is the case, the model of the building is saved in IFC2x2 format. If the latter is the case, the model of the building is imported into ArchiCAD and then saved in IFC2x2 format. A qualified member of the design team defines the thermal "view" of the building geometry with ArchiCAD's IFC2x2 utility (i.e. groups rooms/spaces into appropriate thermal zones). The IFC2x2 file thus becomes the BIM that contains building geometry and the basic definitions of construction materials for the designed building.

The content of the BIM is checked for errors, omissions, interference and contradictory definitions with SMC. In most cases this first requires selection of "constraints" that define the rules and subject of checking from available constraint sets; in some

cases the definition of new sets with CSM may be required. If SMC detects problems, the model of the building is corrected in ArchiCAD and the IFC2x2 file is resaved to be further checked with SMC. This feedback process continues until no further problems are detected in the BIM.

The user of the cost estimation tool (Constructor and Estimator) imports building geometry and the associated basic definitions of construction materials directly from the BIM. Constructor is an application that runs "on top" of ArchiCAD: It is integrated with ArchiCAD, so the import of data from the BIM is actually done with ArchiCAD via its IFC2x2 utility. To create cost estimates, the end user must next import or define "recipes" and "methods" of construction from external data sources, assign construction "locations," and specify resources and unit costs for each instance of a construction element identified in the building geometry. This requires expert construction and cost estimating knowledge. Seamless import of data from a BIM in this process is limited to the import of building geometry and the associated initial basic definitions of construction materials, and does not include definitions of HVAC equipment and systems. The rest of the process is "hard core" cost estimating facilitated by the rules, procedures and requirements of Constructor and Estimator.

The user of the energy performance estimation tool (EnergyPlus) can currently import only building geometry from a BIM. This is accomplished via the IFCtoIDF tool which incorporates BS Pro and imports building geometry as defined in the thermal "view" of the building, simplifies it and translates into EnergyPlus input syntax. The simplification of building geometry includes simplified definitions of slabs, walls, windows and doors, omission of beams and free standing columns, incorporation of other columns into walls, and omission of interior walls defined entirely within the same thermal zone. Definitions of HVAC equipment and systems, as well as occupancy, plug load and operating schedules, can also be imported via the IFC HVAC interface to EnergyPlus *if* they exist in the BIM.

Since no HVAC design tool in North America is currently IFC compatible or indirectly interoperable (see *2.7 HVAC design software* above), EnergyPlus is the only tool that can populate a BIM with such data. Thus the user creates HVAC definitions, schedules and all other data that are necessary to execute the simulation manually or from external data sources using the IDF Editor (a native input tool bundled with EnergyPlus). It is important to note that seamless import of building geometry from a BIM can reduce the effort and the time needed to prepare input for EnergyPlus by 70-80% (Bazjanac 2001), but that it currently works properly only for buildings that do not have complicated or unusual geometry features. (Work to make this process more robust is currently in progress.)

While BS Pro can extract simple and composite constructions from a BIM, IFC interfaces to EnergyPlus currently cannot translate these into appropriate EnergyPlus input format. Nor can they automatically define material properties as required for EnergyPlus. These are all added manually. "Recipes" for cost estimating are usually the most accurate source of information for detailed definition of composite constructions.

Multiple simulations typically result in partial redesign and/or resizing of HVAC equipment and systems. While the IFC HVAC interface can populate a BIM with the original HVAC data and subsequent updates, such data cannot be seamlessly transmitted from the BIM to Constructor.

Tools used in this process are sophisticated and very complex. Their *proper* and effective use, and the generation of *meaningful* results require substantial skill, knowledge and experience. The process requires the participation of highly skilled individuals from different disciplines who are also skilled in the use of specific software. Tasks such individuals perform cannot be successfully done by members of typical A/E project staffs, except for transcription of construction materials and assemblies needed for EnergyPlus.

5 WHAT IS NEEDED IN THE NEAR FUTURE

The process depicted in Figure 5 still involves a significant amount of end user manual intervention that should be automated. With such improvements, a more semi-automated process of generating cost and energy performance estimates using IFC based BIM is depicted in Figure 6.

Reaching the status of the process depicted in Figure 6 will require a few new interfaces as well as enhancements to several existing software applications and interfaces. CAD BIM authoring tools will have to be able to define and write external shading surfaces as such to a BIM. At least one HVAC design tool will have to become IFC directly or indirectly compatible to enable IFC based BIM population with original HVAC design data. This will also make the use of such HVAC design tool much more productive, as its users will be able to seamlessly import building geometry that such tools require and that is currently recreated manually. Constructor and Estimator (and other future IFC compatible cost estimating tools) need an IFC interface that will export detailed materials and constructions data to a BIM and import HVAC equipment data they use in cost estimating. Interfaces to EnergyPlus (and future IFC compatible energy performance estimating tools) will have to be able to import materials definitions and rich composite constructions from a BIM, as well as geometry definitions that specifically describe external shading devices.

Pilot projects are the best mechanism to make the AEC industry in general aware of successes and pitfalls in the deployment of new technology. In this case a pilot project demonstrates how cost and energy performance estimating software can be used to improve design decision making for building designs that are not trivial, and how a BIM can make the use of such software faster and more efficient. While a few such pilot projects have been already completed and a few more are in progress, many more are still needed.

A/E staffs in general do not have the necessary skills to create a BIM and use the "target" software by themselves – few A/E firms have tried this in real, commissioned projects. Only a few software tools in North America qualify as "target" software. This currently leaves A/E firms with virtually no alternative choices in the selection of in-house software that can participate in the process of creating semi-automatic cost and energy performance estimates that draw data from an IFC based BIM. Some of the available software itself is still buggy and sometimes cannot model unusual or complicated features of a building; its use often requires direct technical support from its vendor. The AEC industry software vendor community overall will have to do more than it has traditionally done – it will have to offer more robust products with more functionality and more IFC interfaces.
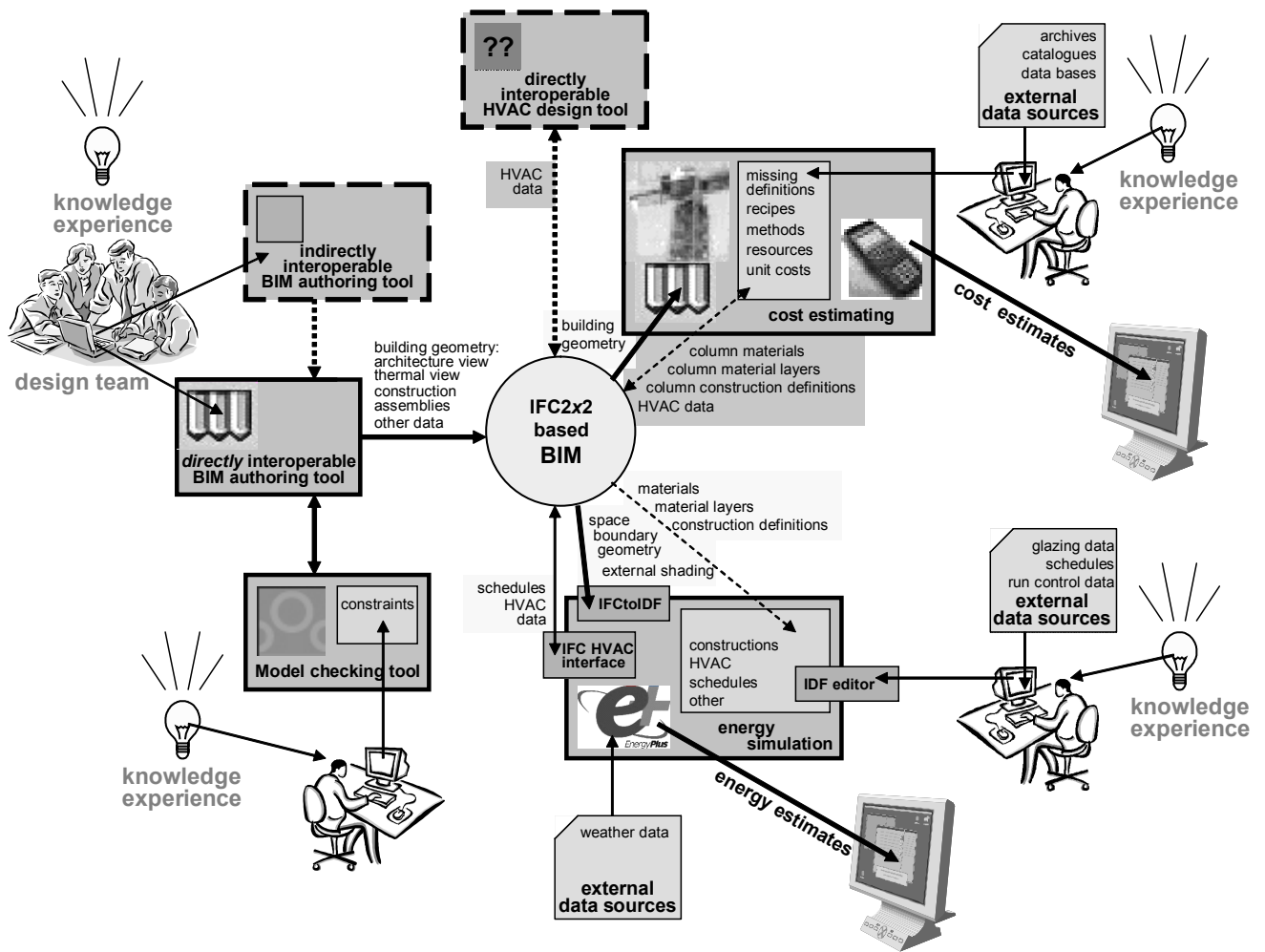
Figure 6. Data generation and flow in a more semi-automated cost and energy performance estimating software environment

A/E firms and their staffs will need immediate, quick and direct help when they encounter problems. That help is already available from the few existing knowledge centers. A knowledge center – at times called a Virtual Building Environment (Bazjanac 2004) – is a place one can go to in order to obtain expert help in the development of an IFC based BIM and in the use of "target" and other industry software. It is also a place where one can test new interoperable software and specialized hardware before acquiring it, witness efficient and effective use of "target" software, learn how to use sophisticated features in software, obtain "work-around" solutions when software cannot do something directly, obtain immediate support from software vendors' technical staffs to fix bugs or provide "special case" solutions, get leads to proper "external" data sources, be informed about "default" values built into software, and much more. In addition, a knowledge center can provide another important service: "neutral source" validation of IFC based BIMs and of cost and energy performance estimates generated with "target" software.

In principle, three such knowledge centers already exist in North America – one is at Stanford Univer-

sity (Center for Integrated Facilities Engineering, or CIFE), one at LBNL (in its Building Technologies Department), and one at the Georgia Institute of Technology (the AEC Integration Laboratory) – and one in Finland (the first formal Virtual Building Environment center at Tampere University). Another one could fairly easily be started at the U.S. National Institute for Standards and Technology (NIST). More are needed, especially those that are not based at academic or research institutions.

6 CONCLUSION

One can generate meaningful cost and energy performance estimates using data obtained directly from an IFC based Building Information Model (BIM) *today*. A BIM cannot, and probably never will, contain *all* data possibly used in generating these estimates; it *does* contain important *reusable* data that can be fetched from it or added to it by *IFC compatible* software.

LEED rating and the quality of cost estimates depend a great deal on the design and performance of energy systems and the building as a whole. Cost

and building energy performance estimating based on information directly obtained from a BIM can be accomplished only by a handful of "single-source" software tools. Vendors of other tools will have to provide IFC interfaces to their tools before these tools can participate in IFC BIM based project data exchange.

Not everyone will be able to use these "new generation" tools immediately, but there *are* some who already can. The tools are very sophisticated and their use requires skills and knowledge not commonly found in the industry. Their use in real life industry projects will initially require the participation of experts who can provide to project staffs the necessary skills and knowledge.

Work remains to be done before A/E firms and their staffs industry wide can readily create a BIM or fully utilize interoperable software. Some of the currently available software needs prompt fixing. Multiple pilot projects should be launched in the immediate future (a few have already started). Initial support should be provided to existing and new knowledge centers.

To provide the necessary information for meaningful cost and energy performance estimating, some design decisions traditionally made later need to be made during schematic design. Systems like foundations, MEP, electrical, fire safety, security, landscaping and others need to be outlined early enough in sufficient detail to provide meaningful and usable information needed by the estimating and simulation tools. In the future, project consultants who provide such design services should be contractually bound already in schematic design, and contractually required to provide the necessary design information in support of cost and energy performance estimating in that phase of design.

7 ACKNOWLEDGMENTS

REFERENCES

Bazjanac, V. 2001. Acquisition of Building Geometry in the Simulation of Energy Performance. In R. Lamberts et al. (eds), *Building Simulation 2001, Proc. intern. conf., Rio de Janeiro,* Vol. 1: 305-311. ISBN 85-901939-2-6.

Bazjanac, V. 2004. Virtual Building Environments - Applying Information Modeling to Buildings. In A. Dikbaş and R. Scherer (eds), *eWork and eBusiness in Architecture, Engineering and Construction, Proc. fifth Euro. conf. product process modelling, Istanbul, TR:41*-48. Balkema. ISBN 04 1535 938 4.

Geopraxis, 2004. *Green Building Studio AEC Design Practice Study 2004 - Final Report. PG&E Savings by Design Program*, 10 August 2004.

Howell, I. and B. Batcheler, 2004. *Building Information Modeling Two Years Later - Huge Potential, Some Success and Several Limitations*. Newforma white paper.

Hui, S.C.M, 2004. Building Energy Simulation Tools. University of Hong Kong.
http://www.arch.hku.hk/research/BEER/best.htm.

Laiserin. 2002. Comparing pommes and naranjas. *The LaiserinLetter™. Issue 15.*
http://www.laiserin.com/features/issue15/index.php.

Laiserin, J., 2005. LaiserinLetter.
http://www.laiserin.com/archive/index.php.

LEED 2005 (Leadership in Energy and Environmental Design). *Green Building Rating System*.
http://www.leedbuilding.org.

Moravec, F. J., 2003. Cost Effective Delivery of the Capital Construction Program. General Services Administration, Memorandum for Assistant Regional Administrators, PBS.

OzGrid Business Applications, 2004.
http://www.ozgrid.com/Services/excel-Add-in-cost-estimators.htm.

TAG, 2003 (IAI Technical Advisory Group). Report to the IAI North American Chapter's Board of Direction, December 2003.

U.S. Department of Energy (DOE), 2005.
http://www.eere.energy.gov/buildings/tools_directory/.