

1 **Dynamic – Building Information Modeling (Dynamic-BIM):**
2 **An Interactive Platform for Building Energy Engineering Education**

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21 **ABSTRACT**

22 Building Information Modeling (BIM) allows for the efficient program
23 management of building design, construction, and operation. While powerful, BIM
24 has several limitations with existing environments such as, disintegrated tools and
25 technologies; static and/or single user environments; lack of a system based on just
26 applied sustainability concepts, among others. This chapter discusses the
27 development of a Dynamic-BIM platform, a multi-user integrative, collaborative, and
28 extensible environment that enables energy and environmental impact. Additionally,
29 this platform provides the much needed framework for a dynamic and interactive
30 platform for building energy engineering education. The platform uses a generic
31 reference architecture that is applicable to tighter coupling of integrative and
32 collaborative environments for buildings and their environment. An extended version
33 of this platform tracks all types of energies used by campus buildings representing a
34 “campus energy map,” both on a monthly and annual basis. Two applications of this
35 platform are discussed in this chapter: (1) a prototype implementation of University
36 of Florida (UF) campus buildings where energy data (electricity, chilled water, steam,
37 and water) is visualized and (2) a prototype implementation of an educational
38 building in the UF campus where data is collected in real-time and visualized. The
39 learners’ engagement and how they use the tool in the classroom setting to
40 understand energy types and uses of campus buildings are discussed as well.
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45 **BACKGROUND**

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47 Building design, engineering, construction, and operation are complex
48 processes that involve participation of multiple stakeholders in a coordinated manner
49 for efficient use of human and natural resources. As a collaborative environment,
50 Building Information Modeling (BIM) allows for the efficient program management
51 of building design and construction. BIM is widely used for both small- and large-
52 scale projects particularly in facilitating communication and decision-making among
53 project team members. Besides, BIM has rich resource capability to extend to fourth
54 and fifth dimensions, i.e., cost and schedule respectively. Among others, the greatest
55 value of BIM to Architecture, Engineering, and Construction (AEC) industry are
56 fewer errors, improved work quality, and reduction of disputes. Several organizations
57 have directed the use of BIM for new and existing projects and, accordingly, in some
58 cases, developed guidelines for implementation of BIM for new and existing
59 buildings. The United States General Services Administration released the “BIM
60 Guide for Energy Performance” as a method to strengthen the reliability, consistency,
61 and usability of predicted building energy use and energy cost results (GSA, 2009).
62 Others guidelines include, BIM standardization by Finland’s Senate Properties
63 (2007); Statsbygg (2011), the Norwegian government’s key advisor in construction
64 and property affairs; and the American Society of Heating, Refrigeration and Air-
65 Conditioning Engineers’ BIM Standard (2009).

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67 Nevertheless, more work is needed to extend the capabilities of BIM to
68 conduct *detailed* performance analyses related to energy engineering such as energy
69 estimation using hourly energy simulation algorithms particularly EnergyPlus owing
70 to its extensive capabilities; 3D conjugate heat and airflow analysis for design
71 decision-making; data analytics and visualization, etc. Essentially, a dynamic
72 platform that possesses the strengths of BIM within an integrative environment will
73 not only enable rapid multi-scale analysis of building energy, but also provide the
74 much needed framework for a dynamic and interactive platform for building energy
75 engineering education. The development of this dynamic platform requires a
76 combination of both integrative and collaborative environments. While integrative
77 environments enable development of tools, collaborative environments (such as BIM)
78 facilitate data sharing and effective communication among stakeholders. In the case
79 of integrative environments, research efforts started in the early 1970’s to support
80 integration of a variety of tools for assessment of buildings. One critical component
81 to support integration is the standard description of building product models to define
82 individual data objects and relationships to object within the model, typically, in a
83 hierarchical representation. Particularly for built environments, such integration led to
84 the Industry Foundation Classes (IFC) which is based on object-based inheritance
85 hierarchy. This file format provided a common ground for data interoperability, i.e.,
86 enabling data exchange between software. Since the design and implementation of
87 standard product model representation, particularly the IFC, there has been
88 remarkable surge in research efforts to integrate building performance analysis tools.

90 For the purposes of this chapter, it is crucial to understand the development of
91 integration tools. Table 1 lists the various integration tools and frameworks. For
92 assessing their capabilities, integrative tools are discussed using three criteria, namely,
93 tool overview, performance analysis, and schema used. The tool overview criterion
94 focuses on the methodology used in tool implementation, its analysis domain i.e., if
95 the integrated tool is a standalone or web-based, and its abilities to conduct analysis
96 based on artificial intelligence techniques such as simple rule-based, dynamic-
97 constraint based, etc. The performance analysis criterion discusses various tools
98 implemented and access to real-time sensor data. Lastly, the schema used in the tools
99 refers to the product model language.

100
101 **Pre-IFC Integration.** One of the earliest attempts in tool integration is the
102 Integrated Design Databases (IDD) using GLIDE (Eastman, 1979a; Eastman and
103 Henrion, 1997) for design activities related to architecture and engineering. Although,
104 this work did not initially focus on assessing building energy- and/or environmental-
105 impacts, it paved way for the creation of a Design Information System or DIS
106 (Eastman, 1979a). The Design Information System used abstraction hierarchies to
107 support different design operations through analysis and synthesis models. This
108 system not only allowed members of design team to access common data, but it
109 permitted linkages to external analysis programs such as structural, thermal, cost, and
110 piping and distribution sizing. An extension of this system led to Computer Aided
111 Engineering and Architectural Design System or CAEADS (Eastman, 1979b) which,
112 then, emerged as a fully developed system for architectural applications.

113
114 With greater emphasis on building energy efficiency in early 1970's, research
115 focused on promoting energy efficiency at the drawing board, i.e., offering tools that
116 designers can rely for performance related analysis. Notable among them include,
117 Advanced Energy Design and Operations Technologies or AEDOT (Pohl et al., 1992)
118 that used an Intelligent Computer-Aided Design System or ICADS (Pohl et al., 1998).
119 Using a dynamic agent technology, the ICADS was improvised to develop the
120 Knowledge-based Object-Agent Collaboration system or KOALA (Pohl, 1996). At
121 this time, the concept of unified models was used in model representation. These
122 unified models were used to identify design strategies by applying constraints as in
123 the case of ARMILLA (Haller, 1985). Later, an A4 prototype of ARMILLA used a
124 modular building approach (Gauchel et al., 1993).

125
126 In spite of several research attempts in integration tools in this early period of
127 building performance analysis, there was no one binding model representation for
128 data transfer between tools (i.e., researchers were using independently built schema
129 for model representation and, subsequently, data transfer). Each of the tools relied on
130 their own representation, and this posed difficulties for widespread development of
131 tool integration for the purposes of building design and analysis. The development of
132 EXPRESS language and, later, the formalization of STEP provided the necessary
133 standard for such representation and spearheaded the integration efforts as discussed
134 in the post-IFC era below.

135

136 **Post-IFC Integration.** Post- IFC, the integration tools took advantage of the
137 standard product model representation which helped interoperability to a greater
138 extent. The COMBINE (Augenbroe, 1992) and COMBINE-2 (Augenbroe, 1995)
139 projects demonstrated the potential of linking existing tools such as energy,
140 daylighting, and others. Model representation using EXPRESS language and later,
141 the formalization of STEP, and now, the IFC standard, are significant steps in tool
142 integration. EXPRESS language became the binding block of the Knowledge-based
143 Design Support or KNODES (Rutherford, 1993). The Building Design Advisor
144 (BDA) used process-logic control for automating activation processes (Papamichael,
145 1999). A Decision Desktop in BDA allowed designers to conduct multi-criteria
146 analysis based on light illuminance, energy use, etc. Although effective, it did not
147 offer automated geometry design variations, but instead assigned ‘smart’ values from
148 a prototype database. A similar approach was attempted by Soebarto and Williamson
149 (1999) in the development of a Designer Orientated Performance Evaluation
150 approach used ENER-WIN software. This approach performed benefit-cost ratio for
151 multi-criteria energy- and environmental- assessments.

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153 Major advancement in integration tools was realized with SEMPER (Mahdavi
154 et al., 1997). This environment provided an active, multi-aspect design environment.
155 Later, this was expanded to web-based in SEMPER II or S2 (Lam et al., 2004).
156 SEMPER enabled thermal, airflow, thermal comfort, lighting, and Life Cycle
157 Assessment using the Shared Object Model schema. A similar progression was
158 reached with the Design Analysis Integration (DAI) that offered a process-centric
159 workbench to overcome the limitations of the data-centric interoperability approaches
160 (Augenbroe and de Wilde, 2003). The inclusion of temporal databases with IFC to
161 develop an open, dynamic, and temporal building model is yet another attempt to
162 create intelligent, adaptable buildings in the Dynamic Building Model (Gryzbek et al.,
163 2010). In this building model representation, IFC is improvised with dynamic
164 capabilities of temporal databases in order to mine, learn, and dynamically respond to
165 changes in building states.

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167 Recent developments such as the Building Controls Virtual Test Bed or
168 BCVTB (Wetter, 2011), SimModel (O’Donnell et al., 2011), and Simergy (See et al.,
169 2011) represent significant milestones in integration efforts. While BCVTB provided
170 the software environment for co-simulation and more, SimModel is expected to offer
171 interoperability between BIM and energy simulation engines. Further, Simergy is
172 expected to offer an intelligent decision support using EnergyPlus (2012). BCVTB
173 enables co-simulation of analysis programs using a middleware instead of coupling
174 them directly. In the case of the test bed, to give an example, the output of one
175 simulation program can be used as an input into another program during run-time.
176 Yet, runtime data exchange is not a substitute for data interoperability, rather it
177 facilitates co-simulation. Besides, the test bed utilizes Modelica-based (2012)
178 building component libraries. At present, the building component libraries (Wetter,
179 2011) are accessible for simulation via commercial software, such as Dymola (2012).
180 Another recent work is the development of the Cyber-physical Building Energy
181 Management System (CBEMS). This system uses a tiered integrated approach to

182 energy, lighting, and plug-loads estimation integrated with policy learning / artificial
 183 intelligence techniques (Wang et al., 2011). This system supports several protocols
 184 for intelligent buildings such as BACnet, KNX, LonWorks, and ZigBee.

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Table 1. Summary of integration tools.

Integration Tool	Tool Overview			Performance Analysis		Schema
	Approach	Domain	Intelligence	Integrated Tools	Sensors	
IDD using GLIDE	Abstraction hierarchies with analysis and synthesis models	Standalone	Rule-based	-	-	-
DIS & CAEADS	Design exploration using GLIDE and abstract representations	Standalone	Rule-based	Structural, Thermal, Cost, Piping and Distribution Sizing analyses	-	-
AEDOT using ICADS	Routine-based integration using a blackboard.	Standalone	Rule-based	Energy Standards, Building Mass, Daylighting	-	-
KOALA	Constraint- and functionality-based decision support system	Standalone	Object- (dynamic) agent technology	Similar to ICADS	-	-
ARMILLA	Constraint- based (centralized control) unified model; design strategies	Standalone	Dynamic constraint-based	Spatial layout and mechanical systems	-	-
A4 Prototype of ARMILLA [Integrated modular building model approach	Standalone	Dynamic constraint-based	Same as ARMILLA	-	-
COMBINE , COMBINE-2	Integrated environment for energy and HVAC tools in COMBINE. Used Petri Nets concepts in COMBINE-2	Standalone	-	Energy, HVAC Tools	-	EXPRESS, STEP
KNODES	Knowledge-based design framework	Standalone	Knowledge-based system	Natural lighting; Energy (BREDEM); Energy design; Spatial analyzer; Structural; Costing	-	EXPRESS

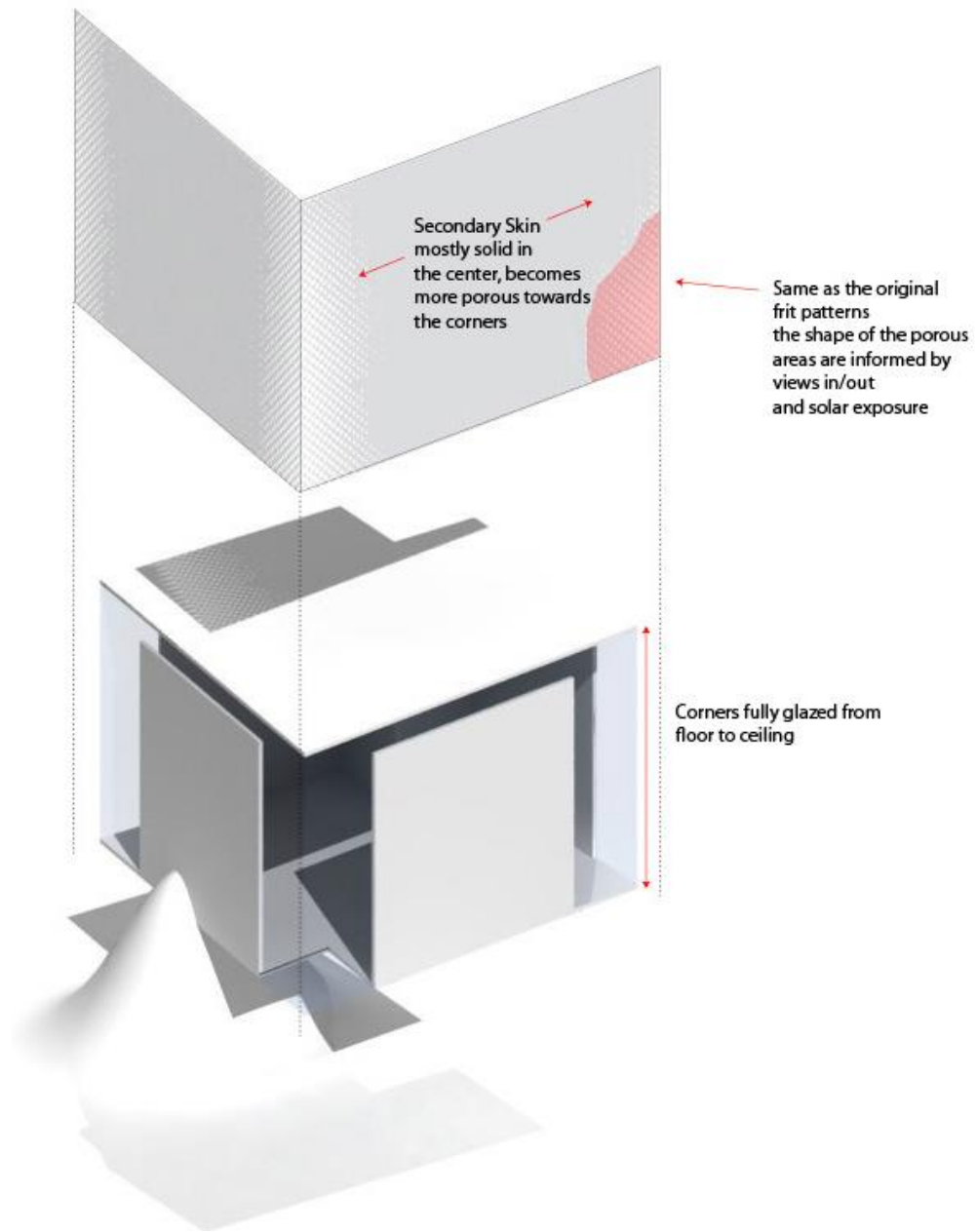
BDA	Integrated environment for design process decision-making	Web-based	Process-logic control for automated activation of processes	Daylight (DElight); Energy (DOE-2); Lighting (Radiance); Airflow (COMIS); Cost (EAM)	-	BDA data metaschema
Designer Orientated Performance Evaluation	Multi-criteria Environmental assessment (uses criteria weightings)	Web-based	Benefit-cost ratio	Energy (ENER-WIN); Emissions; Thermal comfort; Costing; Environmental degradation	-	-
SEMPER	Active, multi-aspect design environment with dynamic links to performance evaluation tools	Standalone	KBES for providing thermal comfort feedback; investigative project technique	Thermal (NODEM); Airflow (Hybrid multi-zone, CFD); HVAC; Thermal Comfort (Algorithmic routines, KBES); Lighting (Radiosity); Acoustics (Hybrid stochastic); LCA (Eco-balance)	-	Shared Object Model
SEMPER II	Web-based active, multi-aspect design environment; used XML for data transfer	Web-based	Same as SEMPER	Same as SEMPER	-	Shared Object Model, XML
DAI	Four-layered process-centric workbench (design information, structure simulation models, analysis scenarios, and software tools)	Standalone (used IBM MQ Workflow engine)	Process modeling and enactment (analysis)	Thermal (EnergyPlus, PMV); Daylight autonomy (IDEA-L)	-	IFC, XML
Dynamic Building Model	Open, dynamic, and temporal building model for intelligent, adaptable buildings	Web-based	Inclusion of temporal databases in IFC to mine, learn, and dynamically respond	Thermal (test case)	Physical sensor	IFC
BCVTB, SimModel, Simergy	BCVTB: Integrated building energy and control systems software;	Standalone	Matlab routines (e.g., optimization) is accessed	Thermal (EnergyPlus, Modelica library); Lighting	Wireless sensor networks (BACnet); Hardware	IFC, XML, BIM import / export; gbXML

	Equation-based object-oriented modeling for building controls; SimModel for data interoperability services; Simergy: Uses a comprehensive GUI, potentially, offering linkages to BCVTB and SimModel.		in BCVTB, provides greater flexibility	(Radiance); HVAC and controls (Modelica library); Controls (Simulink)	connectivity	
CBEMS	Web- and BEMS-based four tier architecture (data acquisition and interface, automatic computing and executing, management, and monitoring)	Web-based	Policy learning (self-learning and self-computing), Nash equilibrium	Energy; Lighting; Plug-loads	Wireless sensor network uses multi-agent distributed systems (supports BACnet, KNX, LonWorks, ZigBee)	XML

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Limitations in BIM

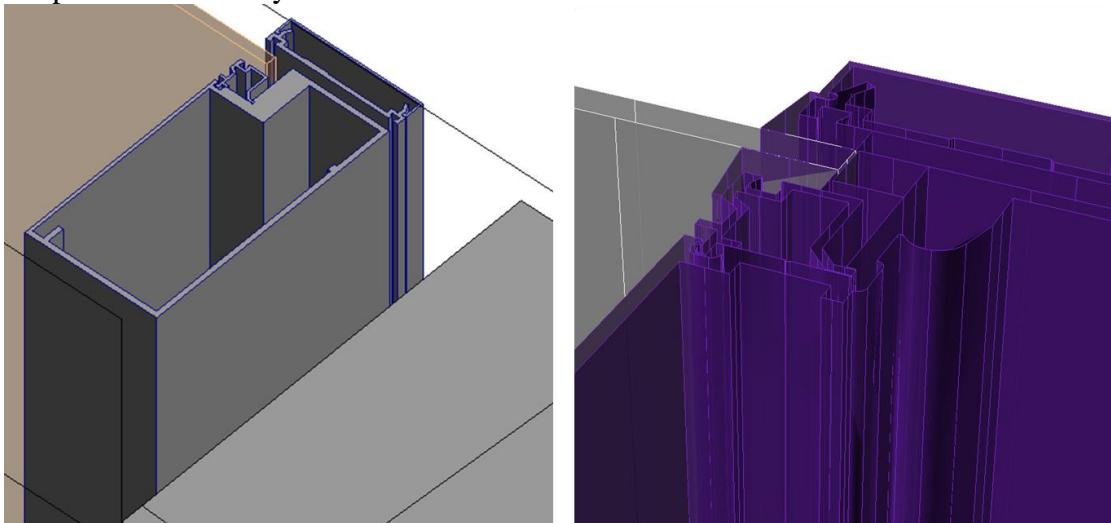
Even with advancements in BIM and building performance assessment tools independently, disconnect between design and analysis is largely prevalent. In some instances, only partial import of models developed in legacy BIM software is possible, thereby, prompting issues related to data transferability and integrity. Take for example, a double-skin façade with perforated external skin where the perforation sizes and shapes vary based on interior space-planning and orientations, figure 1. Although legacy BIM software can model this detail for fabrication purposes, in order to refine this scheme for thermal-airflow efficiency, and later, for adoption, it is essential to evaluate this detail in an integrated fashion using a conjugate 3D heat and airflow, and in relation to the whole building. At present, there are no provisions in BIM tools to conduct such analyses. There are only a handful of programs which are external to BIM that can import this detail for further exploration. In Integrated Environment Solutions’ VE-Pro (2012) software, only a simplified representation of this envelope configuration and/or partial analysis is possible. Also, the BCVTB/Simergy/SimModel environment does not have the capability to import this sample and analyze it for conjugate thermal-airflow effects.



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Figure 1. Sample double-skin façade. (Cade Museum competition project, Gainesville, FL). Image courtesy: MW Bender & Associates and Single Speed Design Architecture.

224 Moreover, some of the existing BIM tools, e.g., Revit MEP (2012), have
225 modeling limitations related to granularity. In the case of modeling fenestration
226 systems, which typically contain glazing, spacer, and desiccant, Revit's minimum
227 tolerance setting (0.8mm) does not capture all minute details of a window-wall
228 interface. Studies have shown issues related to thermal bridging that occur and alter
229 the thermal performance of fenestration systems by up to 15% (Bhandari and
230 Srinivasan, 2012). Conversely, Rhinoceros 3D captures this detail, figure 2, resulting
231 in stark dissimilarities in model generation across BIM tools. Also, at present, none
232 of the window manufacturers have BIM library files of their fenestration products
233 that represent *actual* specifics of the window configuration, i.e., showing glazing,
234 spacer, and desiccant components in their actual sizes. This can be attributed to the
235 lack of demand for these BIM libraries from designers and engineers as there are no
236 currently available tools that can seamlessly conduct 3D heat transfer analysis from
237 within BIM. Currently, thermo-physical properties of windows and walls are input
238 separately in energy and/or airflow analysis programs. In such scenarios, the heat
239 transfers at the window-wall intersections are entirely ignored which may lead to
240 erroneous results (Bhandari and Srinivasan, 2012). In most cases, it can be safely
241 noted that the *use of BIM is akin to typical Computer Aided Design tool*, to generate
242 construction documents, with few exceptions such as clash detection, simplified
243 energy analysis, visualization including renderings, and data repository. In a nutshell,
244 the power of BIM is yet to be unleashed.



245 **Figure 2. Window frame details: (a) Revit MEP, (b) Rhinoceros 3D.**
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247 As noted earlier, simplified performance assessments such as energy, airflow,
248 daylighting, etc., may be conducted directly from within a small number of existing
249 BIM tools such as Revit MEP, Rhinoceros 3D, etc. However, they are *not*
250 comparable to full-scale simulations using standalone analysis tools. There are
251 software tools that allow integrated building performance assessments such as VE-
252 Pro (2012) which allows thermal and energy, three-dimensional airflow, and
253 daylighting analyses; and EDSL's TAS software for integrated thermal and energy,
254 two-dimensional airflow, and thermal comfort analyses (2012). However, these
255 standalone software packages are not BIM tools, although some of these can import
256 BIM files.

257 At the outset, while powerful, BIM has several limitations with existing
258 environments such as, disintegrated tools and technologies; static and/or single user
259 environments; lack of a system based on just applied sustainability concepts, among
260 others. Although past and ongoing research efforts have established a strong foothold
261 in the AEC community, coupling efforts are still evolving. What is missing is the
262 “connecting glue” that supports stakeholders to design, engineer, construct, and
263 maintain buildings and their environment in a single platform such that buildings, as
264 discussed in Srinivasan et al (2012), seek self-sustenance with limited availability of
265 energy and materials. Currently, this lack of integration translates to manual and/or
266 semi-automated procedures of data transfer between tools and, possibly, the creation
267 of redundant and, possibly, erroneous information. More importantly, this lack of
268 integration could, undesirably impact energy efficiency, productivity, and
269 competitiveness in the AEC industry, particularly, since buildings worldwide
270 consume over 40% of all energy, making this a noteworthy problem.

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272 At present, the real-time feedback approaches established in BIM relate
273 entirely to construction project management updates such as project statuses,
274 therefore, current BIM environment may be rendered as “static.” In other words,
275 although BIM comprises of an enormous database of the building structure, it is not
276 active enough to conduct assessment of buildings including implementation of sensor
277 data and/or control algorithms, in real-time. Such an approach could offer optimized
278 solutions for sustainability in building and environment, as well as integrated energy
279 and environmental assessments. With BIM’s widespread adoption by architects and
280 engineers, it must be acknowledged that continuous visualization and monitoring
281 with real-time feedback systems integrated with BIM framework is necessary. A
282 “dynamic” approach to BIM is essential to not only visually track material and
283 energy flows, but also to respond to state changes for immediate feedback and action.

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285 Furthermore, one of the critical components of sustainability is to enable all
286 stakeholders to perform analyses, and to share and access information in an equitable
287 manner with the aid of new technological developments. By extending the current
288 capabilities of BIM, stakeholders can efficiently meet sustainability goals for their
289 buildings. The estimated lifetime of an “as-built” BIM is one to three years, however,
290 in most cases, BIM files are typically shelved after construction. To extend the life of
291 BIM as well as to alleviate the issues of integration within a single platform, a novel
292 Dynamic-BIM platform was proposed and developed. Among others, this platform
293 will integrate to the BIM environment which is all too familiar to all stakeholders,
294 and is currently the norm for most building projects worldwide. Such an approach
295 will lessen the hassle of hopping from software to software or worrying about the
296 limitations of one software over the other, including interoperability issues, or turning
297 to the basics of new software.

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302 This chapter discusses the Dynamic-BIM platform, a multi-user integrative,
303 collaborative, and extensible environment that enables energy and environmental
304 impact analysis and visualization of buildings and environment. The platform uses a
305 generic reference architecture that is applicable to tighter coupling of integrative and
306 collaborative environments for buildings and their environment. In addition, three
307 applications of this platform are discussed in this chapter: (1) a prototype
308 implementation of University of Florida campus buildings where energy data
309 (electricity, chilled water, steam, and water) is visualized and (2) a prototype
310 implementation of an educational building in the University of Florida campus where
311 data is collected in real-time and visualized.

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314 **DYNAMIC-BIM PLATFORM**

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316 The critical component of the Dynamic-BIM platform began with the
317 selection of an environment for seamless domain modeling, simulation, and
318 visualization. That is, the environment selected for the Dynamic-BIM platform must
319 suit the functional requirements as well as suitably fit in the overall system
320 architecture. In the development of Dynamic-BIM environment, one of the early
321 investigations tested the bi-directional data transfer between BIM and building
322 performance assessment tools, more specifically, the Revit/Ptolemy interface. In a
323 typical BIM to Building Energy Modeling (BEM) workflow, the necessary data input
324 for energy analysis is parsed from a BIM to a BEM engine. BEM to BIM workflow
325 transfers energy analysis data back to BIM for visualization. As a test, a Revit plugin
326 was developed to connect the Revit software and Ptolemy model in order to assess
327 forward and backward data transfer capabilities. The Ptolemy model was a modified
328 base model from BCVTB. The test partially succeeded in transferring data from Revit
329 to energy analysis via BCVTB. The energy analysis results were visualized in Revit
330 using simple room geometry. For BEM execution, an automated EnergyPlus file
331 generator from gbXML was developed and tested for simple geometries, and for the
332 purposes of ensuring availability as an open-source tool. Currently, the EnergyPlus
333 file generator does not export system-level information which, for this experiment,
334 was manually inputted.

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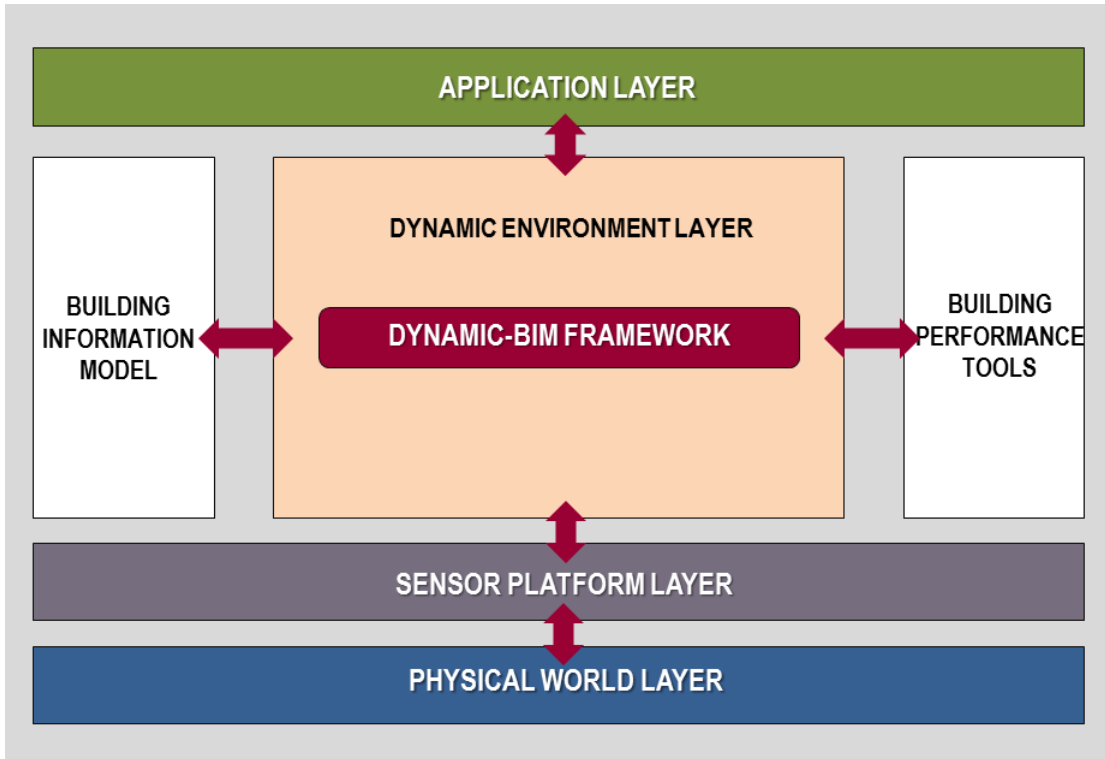
336 Preliminary tests showed that, for multi-user interaction and visualization in
337 Dynamic-BIM, there were several limitations in Revit (Srinivasan et al., 2012; 2013a).
338 Revit plugins have restricted accessibility to external programs owing to lack of
339 multi-thread capability. Per the documentation, Revit's solution to connecting to
340 external programs is to allow developers to create an 'OnIdle' function that Revit will
341 call whenever it is in the 'idle' state. This is not ideal for interactive applications
342 because the 'OnIdle' function is not called at any sort of predictable interval. For
343 example, if the user leaves the mouse cursor still and is not providing any keyboard
344 input, the 'OnIdle' function is never called and, therefore, the visualization is not
345 updated. Presumably, this is because no Revit code is executed unless there is a user-
346 interface event occurring e.g., moving the mouse or hovering the mouse cursor over a
347 button. Additionally, inept text overlays also pose issues related to visualization of

348 analysis results within Revit. One way to overcome such issues is to utilize a public-
349 domain library that eliminates the dependence of software-dependent Application
350 Programming Interfaces and enables data interoperability from any BIM software and
351 using existing functionalities to extract data into the synthesis environment.
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353 As more practitioners leverage computer-based simulation and data analysis,
354 architectures have been developed to support connecting domain-specific modeling
355 tools with the desired simulation and analysis tools and, in turn, with visualization
356 tools. Realizing this pipeline often requires the integration of separate software
357 packages, the coding of custom plug-ins, or both. Examples of such efforts can be
358 found in scientific and engineering domains. Barseghiana et al (2010), for example,
359 created a custom solution for oceanographers. In Kepler, a software package built on
360 top of Ptolemy for creating and executing scientific workflows (Berkley et al., 2004),
361 custom actors were added in order to collect, analyze, and visualize Sea Surface
362 Temperatures obtained from satellite data. Custom visualization features included the
363 ability to register the data points with Google Earth. An example in pharmacology is
364 the Workbench created by Eissing et al (2011) for whole body simulation “across
365 biological scales.” In this Workbench, proprietary modeling and simulation
366 platforms are used to model and visualize the results of biological simulations
367 executed in other programs, including MATLAB.
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369 Dynamic-BIM requires a similar integration of domain modeling, simulation,
370 and visualization. Creation of the domain model can be achieved by mapping the
371 building data in a format that can extract geometry, texture, and material thermo-
372 physical properties. In the case of energy analysis, simulation can be performed in
373 Ptolemy with the help of EnergyPlus actors. However, a graphical and interactive
374 layer to allow a user to change simulation parameters and view the results in real-time
375 situated within the virtual building and from within BIM is required. Two core
376 requirements of this user-interface are the abilities to extract building data and to
377 remotely invoke a simulation. To build the user interface layer, C++ programming
378 language and the Open-source Graphics Rendering Engine or OGRE (2012) were
379 preferred for Dynamic-BIM. C++ was chosen for its speed and power, especially
380 with regards to computer graphics. OGRE was chosen because it is written in C++,
381 open-source, highly customizable, and provided useful high-level functions to
382 abstract low-level graphics rendering code. From any BIM authoring tool, using an
383 external plugin installation, the OGRE-based environment can be accessed. Using
384 this, the BIM is reconstructed geometrically in the Dynamic-BIM environment. Their
385 texture and material thermo-physical properties are also transferred to this
386 environment.
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393 The Dynamic-BIM platform uses a generic reference architecture that is
 394 applicable to tighter coupling of integrative and collaborative environments for
 395 buildings and their environment. It comprises of four layers: physical world layer;
 396 sensor platform layer; dynamic environment layer; and application layer, figure 5.
 397 Buildings and their environment are part of the physical world layer. The sensor
 398 platform layer enables both sensing and activation of moveable systems in the
 399 physical world layer. The most critical of them all is the dynamic environment layer
 400 that houses the Dynamic-BIM platform discussed in the next section. Finally, the
 401 application layer bridges between users and the system using graphical user interfaces.
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405 **Figure 5. Generic Reference Architecture showing Dynamic-BIM platform for**
 406 **tighter coupling of integrative and collaborative environments.**

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408 **DYNAMIC-BIM PLATFORM: ENERGY ENGINEERING APPLICATIONS**

410 Although this platform is extensible, for the purposes of this chapter, two
 411 specific examples at two different scales are provided, i.e., neighborhood- and
 412 building-scales. While for neighborhood-scale, prototype implementation of
 413 University of Florida campus is discussed, for building-scale, this chapter provides an
 414 overview of energy data particularly real-time sensor data. The learners' engagement
 415 and how they use the tool in the classroom setting to understand energy types and
 416 uses of campus buildings are discussed as well.

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420 **Prototype Implementation at Neighborhood-Scale**

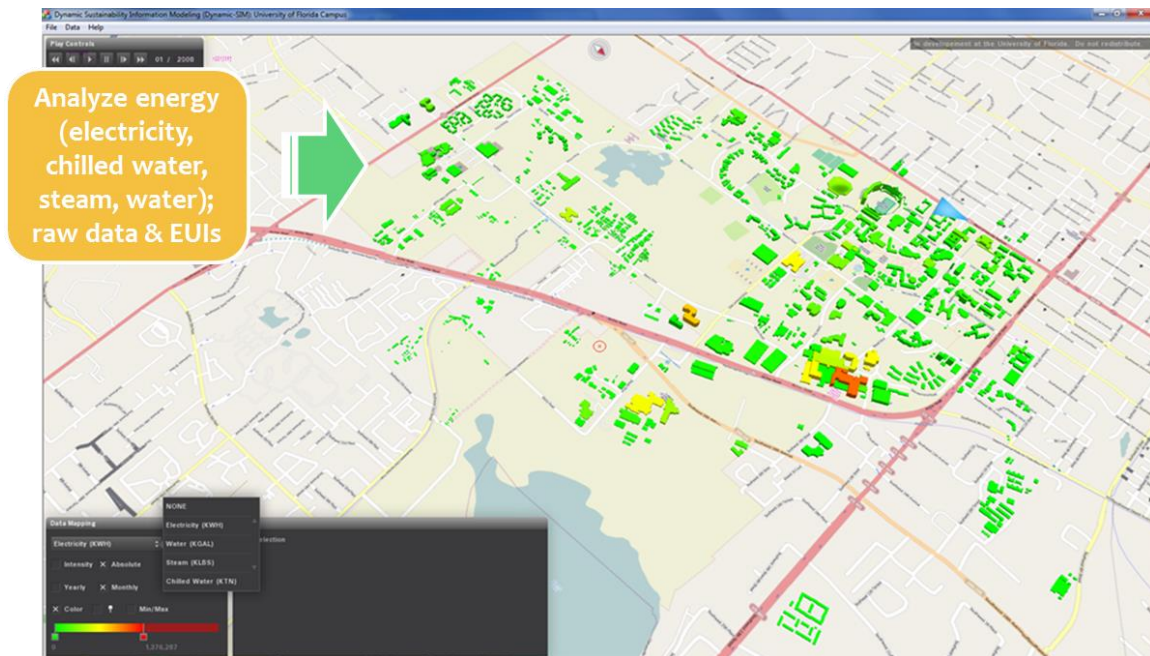
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422 For this prototype, University of Florida campus was chosen. UF campus
423 energy system comprises of two components (1) model / data input interface and (2)
424 Dynamic-BIM environment for analysis, navigation, and visualization. Using the
425 input interface, individual building models and other related data are input in to the
426 OGRE-based system using world coordinates (i.e., latitude and longitude). Currently,
427 historical metered electricity data is used in this prototype. The slider can be used to
428 visualize average energy use of campus buildings, figures 6 to 9. Work is in progress
429 to connect to campus-wide Energy Enterprise System as well as to individual
430 building's meter via BACnet. If sub-meter data (lighting, air-conditioning systems,
431 plug loads, etc.) is available, it can be streamed in real-time to Dynamic-BIM-based
432 energy system.

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434 Currently work is underway to develop electricity usage scrutiny options that
435 will include, (a) enthalpy (outside and use) evaluation, (b) degree-day normalization
436 and analysis, (c) building level energy use intensity, (d) space-use type energy use
437 intensity, (e) average energy use, (f) other uses such as exterior / street lighting,
438 swimming pool heating, etc., for both electricity consumption and demand. Besides
439 electricity, other energy uses (chilled water, water, steam, natural gas, fuel), energy
440 resources (photovoltaic, solar thermal, wind, hydro-electricity), wastewater, etc. will
441 be analyzed using this system. Dynamic-BIM environment and in-built gyroscopes
442 and accelerometers in tablets enable navigation of campus buildings including
443 “flying” above buildings. Future work will test the use of mobile technology,
444 particularly tablets, to “point-and-shoot” at buildings to conduct energy analysis.

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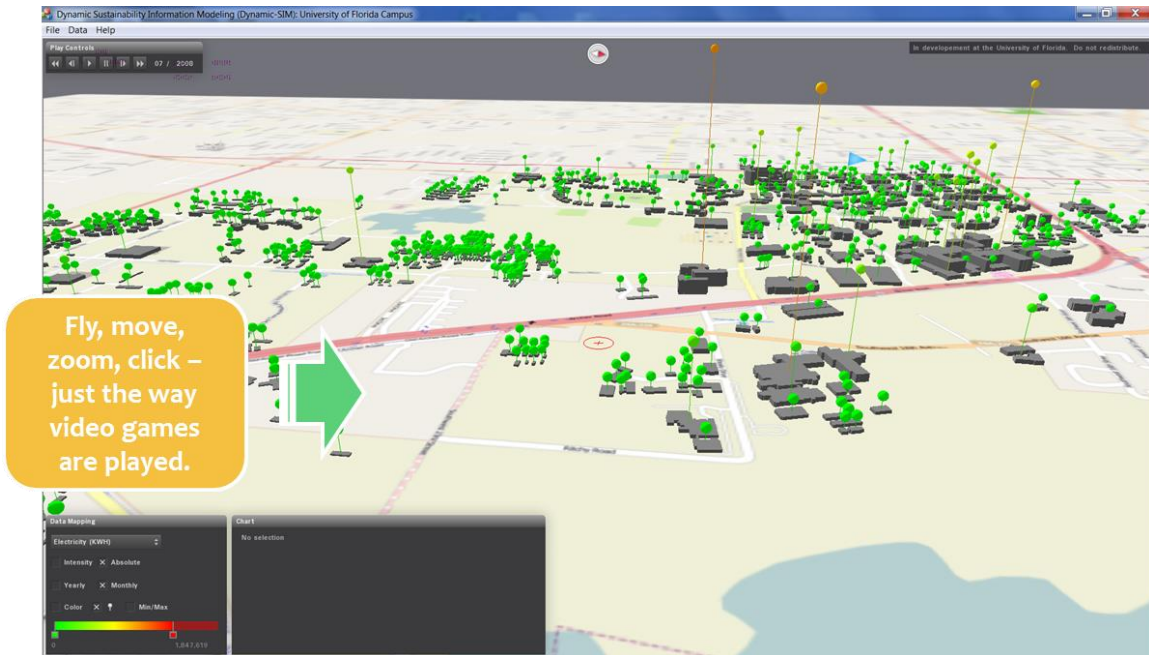
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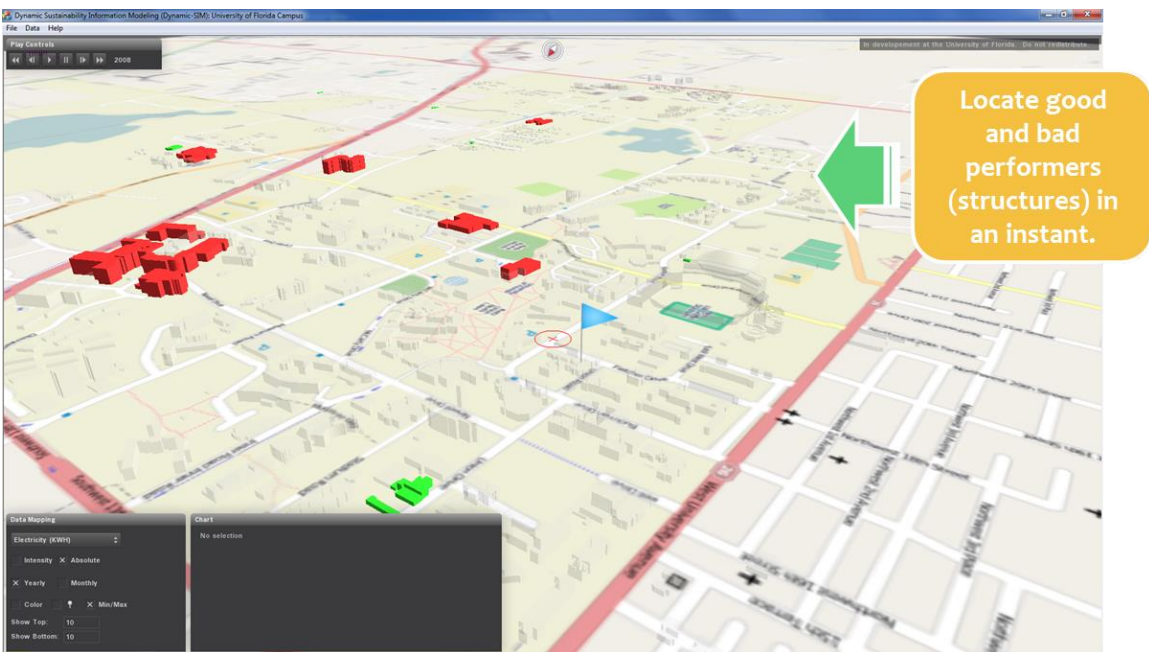
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Figure 6. Bird's eye view of UF Campus, Gainesville, in Dynamic-SIM Workbench. Historic energy use data is used at building level at monthly and annual level.



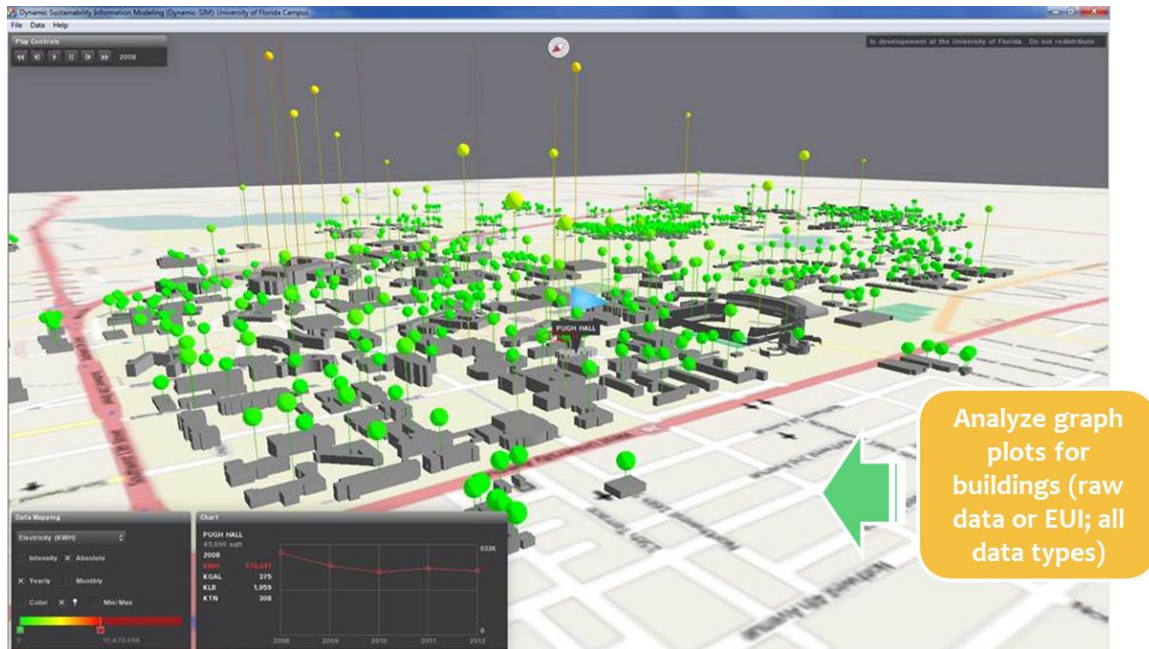
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Figure 7. A “play” button enables engineers to visually evaluate energy use of buildings. A user interface allows data extraction and visualization seamlessly.



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Figure 8. Users can identify good and bad performers in terms of energy use (electricity, chilled water, steam, and water) by month and/or year.



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Figure 9. Individual building’s energy use can be plotted for further analysis.

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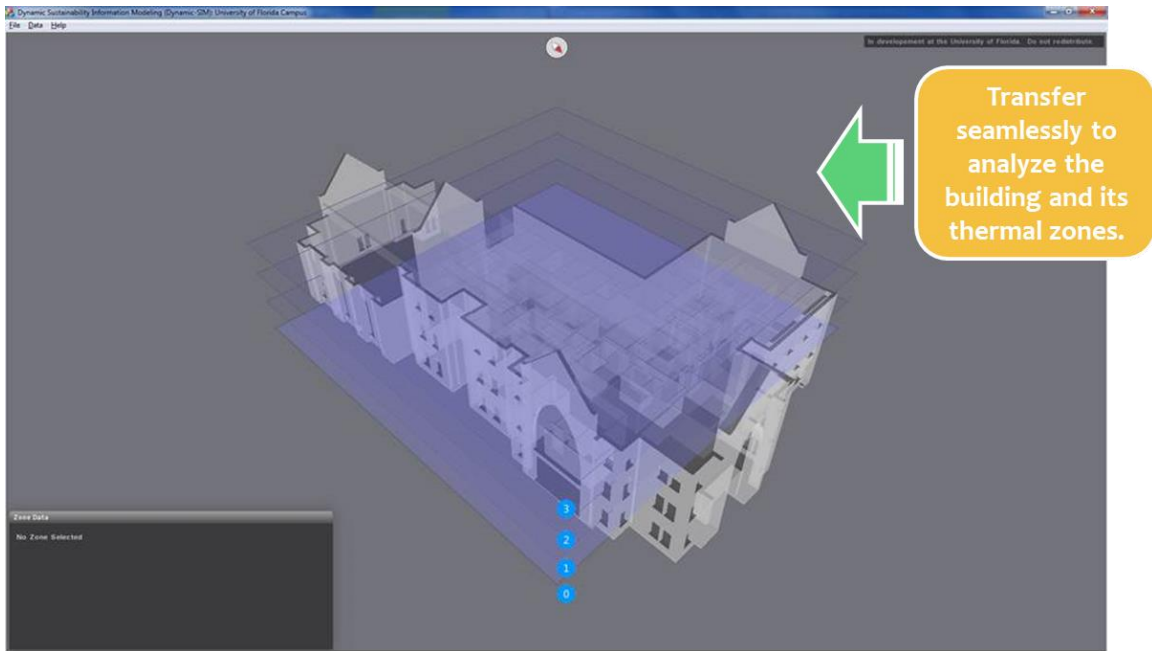
Prototype Implementation at Building-Scale

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Dynamic-BIM platform allows seamless transfer to building-scale. Figures 10 and 11 show building-scale energy visualization of Pugh Hall building situated in UF campus. The location of this building is represented with a blue-colored flag in figure 9. A plugin was developed that extracted geometry and material data into a format that can be used in the OGRE-based environment. The first step of geometry extraction included sorting out the selected “elements” (i.e., walls, roofs, beams, etc.) and “family instances” (i.e., doors, windows, etc.); which were then transformed into “geometry object.” Each of the geometry objects were, then, analyzed to retrieve all “solid objects” that consisted of faces and edges. All the faces and edges of a solid were triangulated and tessellated respectively to extract the nodes. Finally, the surfaces were mapped into regions. Piecewise Linear Complex (PLC) and the mapping were saved in “.ply” file type, which were then imported to the Dynamic-BIM environment layer for visualization. As illustrated in figure 10, the in-built plugin flawlessly exports the geometry from BIM to aid interoperability with Dynamic-BIM platform.

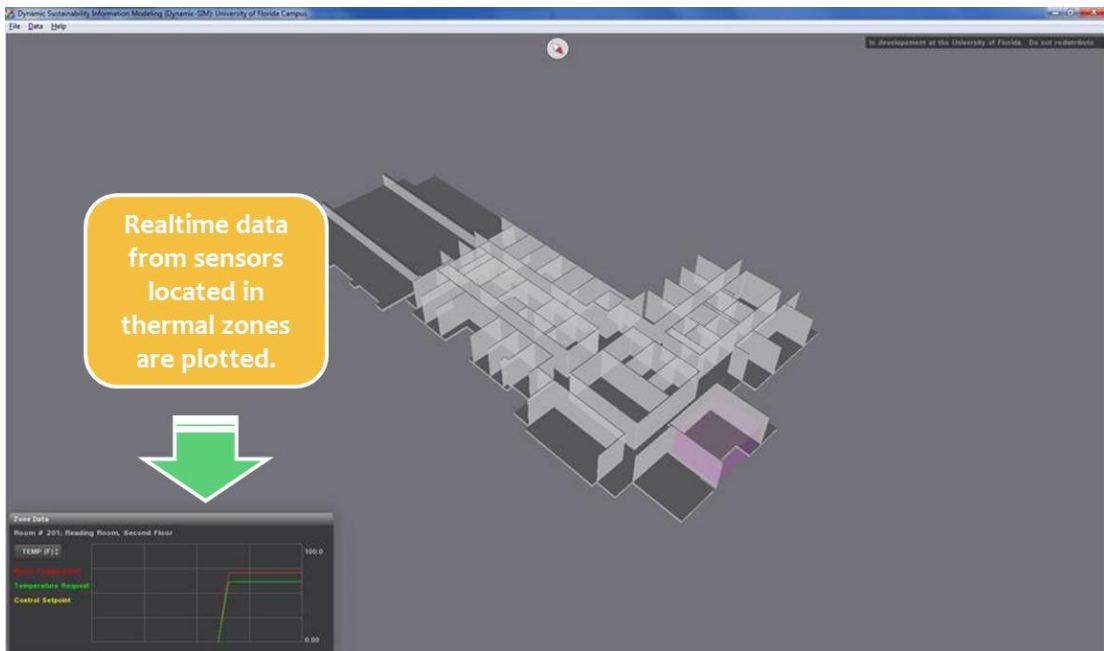
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As a next step, users can engage with the building in several ways particularly moving to different floor plans that show thermal zones. Figure 11 shows an example thermal zone in level two of Pugh Hall. Clicking the thermal zone shows real-time sensor data of several parameters including indoor air ambient temperature, request temperature, airflow rate, Variable Air Volume system vane position, etc. Future work will integrate Fault Detection and Diagnosis (FDDs) at building system- and component- levels, and forecasting algorithms.



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Figure 10. For building and HVAC zone level data extraction, individual building geometry was extracted using a plugin developed in-house, and seamlessly imported into the platform.



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Figure 11. Real-time data from sensors situated in buildings (specific zone under investigation is colored) can be plotted as well.

502 **CONCLUSIONS**

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504 This chapter discussed the development of Dynamic-BIM platform that is an
505 integrative, collaborative, and extensible environment. In addition, this chapter
506 discussed two applications of the framework namely, (1) at neighborhood-scale, a
507 prototype implementation of a campus energy map where data is collected,
508 assimilated, analyzed, and visualized; and (2) at building-scale, a prototype
509 implementation of Pugh Hall building in UF campus showing real-time sensor data of
510 a thermal zone. Among others, one of the key feature of this platform is intuitive user
511 engagement of building energy data using device-specific sensor activation, for
512 example, using of gyroscopes and accelerometers to “fly” or “walk” around buildings.
513 Besides, seamless transfer from neighborhood- to building-scale is an important
514 factor for active user engagement since users can “pin-point” and “click” the building
515 to visualize detailed building thermal zones for further investigation. Preliminary
516 works in the integration of 3D heat transfer (Srinivasan et al., 2014) and
517 environmental analysis is underway (Srinivasan et al., 2013b; Srinivasan and Moe,
518 2015).

519 Greater tool integration specifically, real-time physical sensors, actuators,
520 controllers, and control algorithms will enable on-the-fly simulations that can be
521 conducted to design, operate, and maintain low energy buildings and beyond. In other
522 words, a comprehensive commissioning exercise is feasible using Dynamic-BIM
523 framework to save considerable time and effort. Visualizing, analyzing, and
524 controlling building and its systems in a virtual environment will allow most of the
525 necessary commissioning process to be conducted at ease. This not only extends the
526 life of an “as-built” BIM, but also offers greater flexibility in conducting ongoing
527 continuous commissioning. Also, currently, communication between the Dynamic-
528 BIM prototype and Ptolemy is achieved through ports on the same machine. As we
529 develop further, the ports approach could be potentially expanded to afford
530 communications between different machines over the Internet. Such an approach
531 would enable running the Dynamic-BIM in portable devices to support Virtual
532 Commissioning (vCx) and Virtual Continuous Commissioning (vCCx) and fault
533 detection of existing buildings. Other Dynamic-BIM framework applications include
534 passive solar building design and construction; Net Zero building design and
535 construction; real-time energy analysis of existing buildings; and auto-calibration of
536 building energy performance, to name a few.

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