Chapter 8
Simulation-Based Architectural Design

Rhys Goldstein and Azam Khan

Abstract In recent decades, architects have turned to computer simulation with the hope of designing more functional, sustainable, and compelling buildings. In such efforts, it is important to regard buildings not merely as static structures, but rather as complex dynamic systems driven by highly stochastic elements including the weather and human behavior. In this chapter, we describe how simulation has impacted architectural design research and practice. A multitude of simulation tools have been developed to model specific aspects of a building such as thermodynamics, daylight, plug loads, crowd behavior, and structural integrity under internal and external loads. Yet numerous challenges remain. For example, although many factors influencing buildings are interdependent, they are often analyzed in isolation due to the development cost associated with integrating solvers. A systems approach combining visual programming with state-of-the-art modeling and simulation techniques may help architects and building scientists combine their expertise to produce integrated complex systems models supporting emerging paradigms such as generative design.

Keywords Architecture · Building simulation · Building science · Energy modeling · Sustainability · Systems approach · Discrete event simulation · Design tools · Computer-aided design · Building information model · Heat transfer · Occupant behavior · Daylight simulation · Co-simulation · Model integration · Visual programming · Dataflow programming · Parametric design · Generative design · Performance metrics

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8.1 Introduction

In Chap. 1, Ören et al. provide a number of reasons why simulation is used in general, and many of these reasons apply to the design and optimization of functional, cost-efficient, safe, healthy, sustainable, and visually compelling buildings. Simulation is often used when the real system does not exist, which is necessarily the case when a new building is designed. Simulation is also used when the real system is too slow; thermal performance and daylighting require at least year to properly observe, which is inconveniently long when designing a retrofit for an existing building. Simulation is used when physical experiments are dangerous, unacceptable, or costly, all of which dictate that we should not wait for a building to collapse before simulating its structural integrity under internal and external loads. Finally, simulation is used when the variables of a system cannot be controlled. Two significant, highly stochastic variables influencing the performance of a building are the people who occupy it and the weather. Neither human behavior nor the weather can reasonably be controlled for experimentation purposes, yet a wide range of behavioral patterns and environmental conditions can be tested in a virtual setting.

The physical complexity of a building is evident by simply looking at a *building information model* (BIM) such the one shown in Fig. 8.1. These models, which now enjoy widespread use in the architecture, engineering, and construction

Fig. 8.1 A building information model (BIM) representing the 210 King Street East heritage building in Toronto, Canada

(AEC) industry, combine core building elements such as walls, slabs, windows, and doors with more detailed elements such as furniture, lighting fixtures, and heating, air-conditioning, and ventilation (HVAC) components. By incorporating properties such as materials and room types, BIMs have the potential to supply much of the static information required for highly detailed building simulations. However, buildings should be regarded not as static structures containing physical objects, but rather as dynamic systems involving numerous interacting forces and active entities such as the outdoor climate, electrical/mechanical equipment, and human occupants. The many processes that unfold throughout a building's lifetime give it an additional level of complexity that is only partially accounted for by the simulation tools currently available to architects.

In this chapter, we review some of the most prevalent simulation tools used in building design and engineering practice (Sect. 8.2), highlight a sample of recent and ongoing research efforts in the field (Sect. 8.3), and discuss the potential role that state-of-the-art modeling and simulation (M&S) techniques might play in helping various stakeholders collaborate in the development of next-generation simulation-based design tools (Sect. 8.4). A systems approach for developing building simulation software—based on research from the M&S community—would support the integration of both existing and future models of building thermodynamics, lighting, and occupant behavior. It would also ease the exploration of emerging design paradigms such as those involving the automatic generation of design options, referred to as *generative design*.

Buildings have a tremendous impact on the natural environment, accounting for 41% of all energy consumption and 72% of electricity use in the United States (Livingston et al. 2014). Moreover, they have a less quantifiable but equally significant effect on human experience, as in today's society people spend much of their time in and around buildings. Decision support for building design is therefore one of the most potentially beneficial of all uses of simulation.

8.2 Current Simulation Tools for Architecture

A wide variety of building simulation tools exist for assessing various aspects of buildings. Focusing first on energy-related software, there are 147 tools currently listed in the Building Energy Software Tools Directory (BEST-D). Many of these tools, however, are based on a few core simulators, such as Radiance (Ward 1994) for lighting and EnergyPlus (Crawley et al. 2001), DOE-2 (Curtis et al. 1984), or ESP-r (Aasem et al. 1994) for whole building energy simulation.

To perform an analysis using a detailed BIM and one of the whole building energy simulation tools, the BIM must first be converted into an energy analytical model. In this highly simplified type of model, buildings are represented as networks of polyhedral spaces, each assumed to have a uniform temperature (Clarke 2001). Large rooms such as corridors or atria can be converted into several adjacent spaces separated by arbitrary boundaries, allowing temperature to vary in steps within the indoor area. Surface elements of various materials and thicknesses resist the flow of heat among spaces separated by walls, slabs, and other physical barriers. The mathematics underlying this basic method was largely developed prior to the 1990s when the limited availability of computing power necessitated such approximations. Despite substantial increases in computing resources and decades of subsequent building simulation research, the early approximations remain in use to this day. Fortunately, the task of converting detailed architectural models into simulation-ready energy models is becoming increasingly automated. Figure 8.2 shows the spaces and surface elements of an energy model created automatically from a BIM.

Conveniences such as automated BIM-to-energy-model transformation encourage architects to incorporate technical analyses traditionally performed by engineers in later stages of the building design process. Because many of the decisions that affect the energy efficiency of a building are made by architects at the early design stage, the increased use of energy simulation by designers is seen as a promising strategy toward realizing more sustainable built environments. As emphasized by Bazjanac et al. (2011), challenges such as missing data exist in providing designers with accurate whole building energy results. Indeed, Berkeley et al. (2014) find that even professional energy modelers produce dramatically divergent estimates given the same building and the same modeling tool, highlighting a general need for future developments in building energy simulation software.

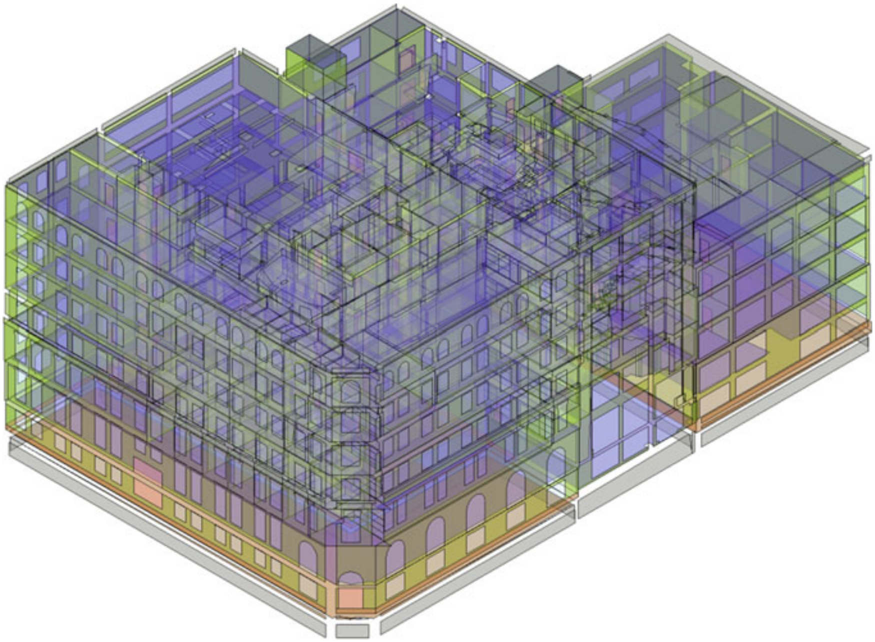


Fig. 8.2 An energy analytical model of the 210 King Street East building created automatically within the BIM-authoring tool Autodesk Revit 2016

Aside from energy-related analyses, simulation has a number of applications in building design and engineering. These include traditional uses such as structural analysis, as seen in Fig. 8.3, and more recent applications such as the multi-agent simulation of crowds for predicting issues related to pedestrian flow or building evacuation. Figure 8.4 shows a snapshot of a multi-agent simulation performed

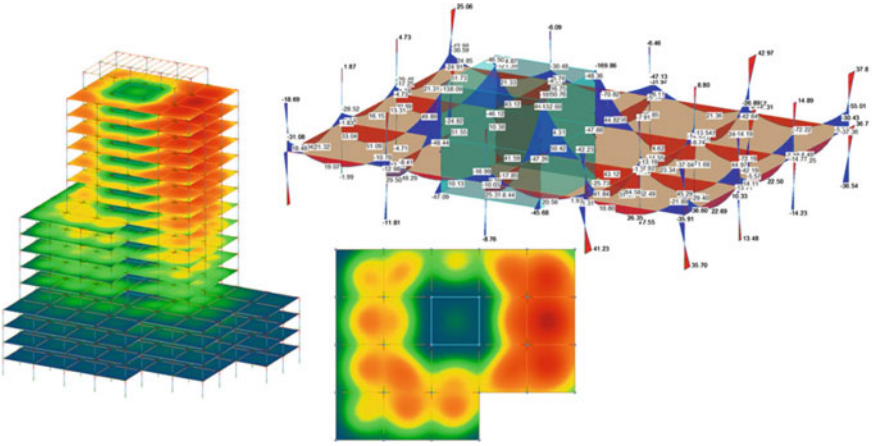


Fig. 8.3 Structural analysis results produced by the Revit BIM-authoring tool

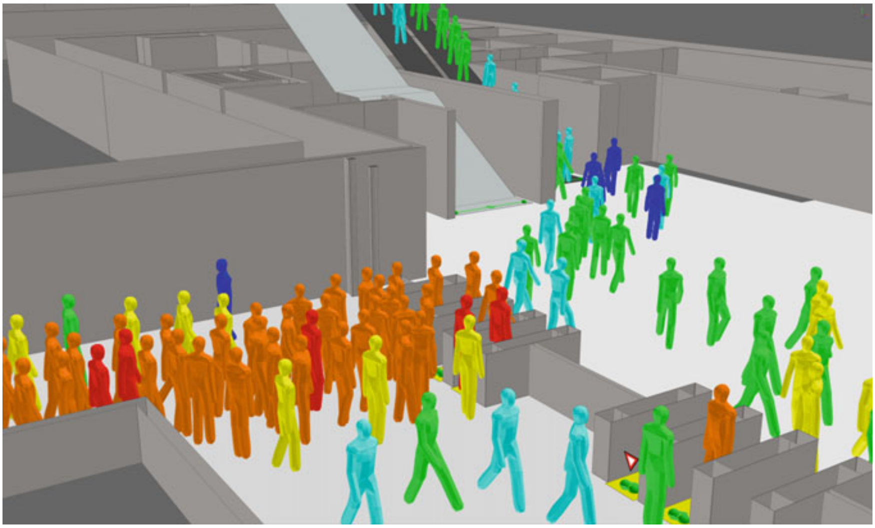


Fig. 8.4 Multi-agent crowd flow simulation performed by the MassMotion design tool (Image courtesy of Erin Morrow, Oasys/Arup)

using the commercial tool MassMotion (Morrow 2010; Morrow et al. 2014), intended for the design of transportation hubs, healthcare facilities, arenas, and other built environments where crowd behavior demands careful attention.

8.3 Architectural and Building Science Research

The large and growing body of research into simulation-based building design can be regarded as occurring within two mostly distinct communities: one primarily involving architects, the other engineers.

Architectural researchers who investigate simulation and other computational methods present their work at designer-oriented venues such as the ACADIA conferences (ACADIA: Association for Computer-Aided Design in Architecture), CAAD Futures (CAAD: Computer-Aided Architectural Design), eCAADe (Education and research in CAAD in Europe), CAADRIA (CAAD Research in Asia), Smartgeometry, and Rob|Arch (Robots in Architecture). In addition to structural and environmental performance, much attention is paid to qualitative measures such as building aesthetics and the manner in which humans perceive, experience, and respond to the built environment. In addition, researchers in this area are becoming increasingly interested in how emerging fabrication techniques, such as the use of robots, can aid the realization of historically intractable designs.

On the engineering side, research into simulation-based building design is generally referred to as building science. One of the primary goals of this research community is to optimize building performance, essentially maximizing the comfort of a building's occupants while minimizing both operational costs and the building's negative impact on the natural environment. Much of the work is presented at the regional and international conferences of the International Building Performance Simulation Association (IBPSA). An international IBPSA conference occurs every two years (recently 2013, 2015, etc.), and the regional conferences around the world are typically hosted on the alternate years. A comprehensive overview of the state of the art in this area can be found in *Building Performance Simulation for Design and Operation*, edited by Hensen and Lamberts (2012). The books' chapters provide a nearly complete list of the domains in which members of the community specialize, including weather, occupant behavior, heat transfer, ventilation, occupant comfort, acoustics, daylight, moisture, HVAC systems, micro-cogeneration, building operations, and government policy pertaining to buildings and energy.

Although most research efforts relevant to simulation-based building design tend to fall into one of the two broad but relatively distinct disciplines, it is well understood that the overarching goal of improving the built environment and making it sustainable is shared among architects and engineers, and requires collaboration among all stakeholders. Hence there are many who present their work at both the designer-oriented and engineer-oriented conferences (i.e., ACADIA and IBPSA), facilitating the exchange of ideas between communities. Since 2010 there has even been a venue—the Symposium on Simulation for Architecture and Urban Design (SimAUD)—largely dedicated to promoting discussion between designers and building scientists, with simulation tools and techniques serving as a common focus.

In the remainder of this section, we highlight a small sample of recent academic research presenting new ideas and recently developed tools that advance the use of simulation in building design. All of these works feature elements familiar to the general M&S community, including modeling languages, modern computing technology, and co-simulation.

8.3.1 Example of Occupant Behavior Research

Schaumann et al. (2015) propose a graphical modeling language for creating narratives that drive the behavior of simulated occupants in not-yet build environments. The focus is on hospital design, for which architects need to understand the complex reoccurring patterns of behavior exhibited by interacting doctors, nurses, patients, and visitors. An example of a narrative is the checking of a patient by a doctor–nurse team. By visualizing a multi-agent simulation of this routine, as shown in Fig. 8.5, a designer may gain insights into whether a particular design option promotes the efficient performance of this activity, or hinders it with an inefficient layout or with probable interruptions by hospital visitors.

Multi-agent approaches such as that of Schaumann et al. (2015) represent a radical departure from the current standard practice in whole building energy

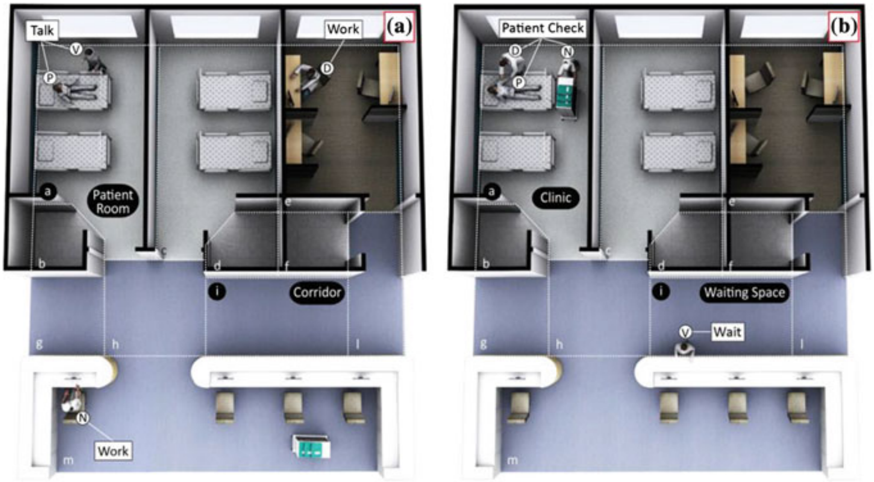


Fig. 8.5 Visualization of occupant behavior in a hospital environment. From Schaumann et al. (2015); reprinted with permission from the authors

modeling, where occupant behavior is modeled using fixed profiles. These profiles typically give aggregated hourly information about the degree to which a space, electrical appliance, or building system is used. The most prominent examples of these profiles are those found in ASHRAE (2004) and subsequent versions of Standard 90.1. Although fixed profile models enjoy widespread use, higher fidelity behavioral models would accommodate new quantitative analyses—such the evaluation of automatic lighting systems based on motion detectors—as well as qualitative investigations that would likely appeal to architects. As mentioned in Sect. 8.2, multi-agent simulation tools are available for pedestrian flow and evacuation, but less so for other normal day-to-day activities of people in buildings.

8.3.2 Example of Daylight Simulation Research

Jones and Reinhart (2015) introduce a new tool called Accelerad, which combines GPU technology with other optimization techniques to perform daylight simulation up to 24 times faster than Radiance with similar areas. Results for two indoor environments are shown in Fig. 8.6. This research takes advantage of two broad opportunities in the discipline. First, it exploits computing technology that has emerged after much of the core research on conventional energy simulation tools was conducted; that is, technology such as the GPU, developed during the 1990s or later. Second, it aims to satisfy the needs of architects, as opposed to engineers, in this case by delivering the speed necessary to gain rapid feedback and explore a greater number of design options.

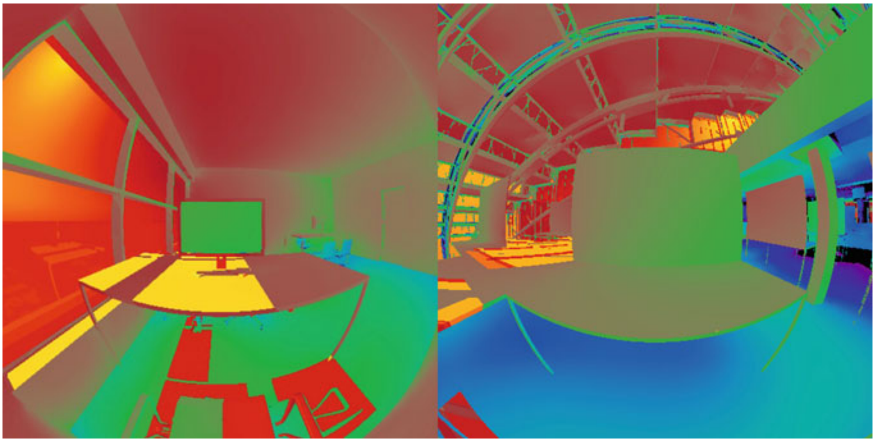


Fig. 8.6 Daylight simulations performed by the Accelerad using GPU technology. From Jones and Reinhart (2014); reprinted with permission from the authors

Table 8.1 External tools linked to or used by the Building Controls Virtual Test Bed (BCVTB) co-simulation environment

External tool	Purpose
Dymola (Modelica)	HVAC system modeling and building controls modeling
Simulink	Building controls modeling
MATLAB	Building controls modeling and data analysis
EnergyPlus	Whole building energy simulation
ESP-r	Whole building energy simulation
Radiance	Lighting simulation
TRNSYS	System simulation
BACnet stack	Data exchange with building automation systems
A/D converter stack	Data exchange with analog/digital converter
Functional Mock-up Units (FMU)	Co-simulation and model exchange

8.3.3 Example of Co-simulation Research

Wetter (2011) introduces the Building Controls Virtual Test Bed (BCVTB), a co-simulation environment linking an assortment of building simulation tools. The environment is built on the multi-paradigm modeling software Ptolemy II (Brooks et al. 2007), uses the Functional Mock-up Interface (FMI) as the standard to support co-simulation (Nouidui et al. 2013), and currently links the tools listed in Table 8.1.

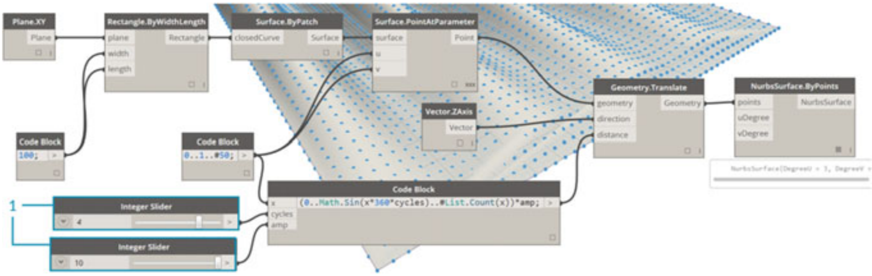
Although the factors influencing buildings are often analyzed in isolation, the impressive number of tools integrated by BCVTB supports the notion that buildings are complex systems involving a variety of interacting processes. No single simulator fully accounts for thermodynamics, light propagation, weather, human behavior, and mechanical systems, and hence co-simulation is perhaps the only way to realize a truly comprehensive building performance model without rewriting a large portion of existing code. Using co-simulation, existing tools share information once per time step, or several time per time step, depending on the strategy adopted by the moderating software. The IBPSA community features several projects in which two tools are integrated via co-simulation, examples being ESP-r & Radiance (Janak 1997) and ESP-r & TRNSYS (Beausoleil-Morrison et al. 2011). The BCVTB is unique in the number of tools it connects, as well as the fact it is intended to support the incorporation of additional tools.

At present, co-simulation appears to be the most popular approach for integrating building simulation algorithms that are not currently implemented in any single tool. In the future, other integration approaches may be beneficial. Goldstein et al. (2013) demonstrate the use of a formalism-based model-independent simulator such as DesignDEVS (Goldstein et al. 2016) as a technological alternative to co-simulation. In addition, adaptive time steps and quantized state solvers are mentioned as mathematical alternatives to the numerical integration strategies which currently dominate building performance simulation research. As explored in the next section, these ideas from the M&S community have the potential to promote collaboration in the development of next-generation building simulation methods, possibly leading to more architect-friendly tools that take advantage of modern computing technology and better accommodate future design paradigms.

8.4 A Systems Approach for Simulation-based Architecture

An opportunity exists to dramatically improve collaboration among architectural researchers and building scientists. This can be done by applying state-of-the-art techniques from the M&S community, which investigates aspects of computer simulation that span disciplines. Our long-term vision is that comprehensive model-dependent simulators such as EnergyPlus and ESP-r could eventually be replaced by a repository of considerably more focused models with a common interface. These new models, contributed by members of the building simulation community, would be integrated in various combinations, and the most successful configurations could be packaged for the benefit of practitioners. A platform of this nature would promote the ongoing improvement of building simulation methods, and allow a much larger group of researchers to participate in the development process. Here we outline a collaborative systems modeling approach particularly well-suited to the discipline of architectural design. Other ideas from the M&S community also merit exploration in this application area.

The underlying principle we follow is to build upon architects' familiarity with certain programming techniques, namely conventional procedural programming and dataflow visual programming. Procedural programming, involving assignment instructions and control flow structures such as "if" statements, is currently taught to students in a wide range of fields including building science and architecture. Although a typical designer has less programming experience than a typical computer scientist or systems engineer, we can rely to some extent on widespread knowledge of basic programming concepts. Dataflow programming, by contrast, is a style of programming that has become especially popular in the architectural research community as a technique supporting *parametric design* (Woodbury 2010). As shown in Fig. 8.7, parametric design tools such as Grasshopper



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0..1..#50;
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(0..Math.Sin(x*360*cycles)..#List.Count(x))*amp;
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Fig. 8.7 An example of dataflow programming in dynamo

(Mode Lab 2015) and Dynamo (Autodesk 2017) allow building geometry to be defined programmatically and modified interactively in visual programming environments integrated with design tools. As observed by Doore et al. (2015) in another discipline (multimedia), the popularity of paradigms such as dataflow programming creates a favorable environment for introducing other M&S concepts.

The systems modeling approach we describe combines dataflow programming with the Discrete Event System Specification (DEVS), the latter of which is a modeling formalism generally applied using procedural code inside composable modules exhibiting a common interface (Zeigler et al. 2000). The overall approach is illustrated by a set of visual interfaces designed by Maleki et al. (2015), some of which are shown in Fig. 8.8. The dataflow elements, appearing at the left and right sides of the interface, are responsible for the initialization of a simulation as well as the aggregation of its results into performance metrics and other statistics. The DEVS elements, placed in the central column of the interface, handle the simulation itself, which captures the evolution of a real-world system over time. As is common among modeling paradigms from the M&S community, scalability is achieved in part via the use of hierarchies. The overall interface represents a *system node*, and the four central nodes within are also system nodes that potentially encapsulate their own dataflow and DEVS elements.

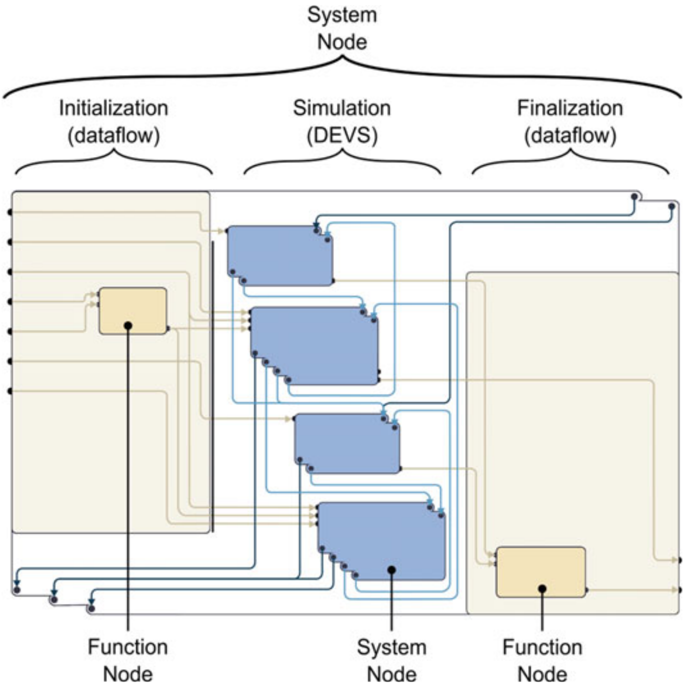

Fig. 8.8 Visual interface mockups combining dataflow and DEVS elements

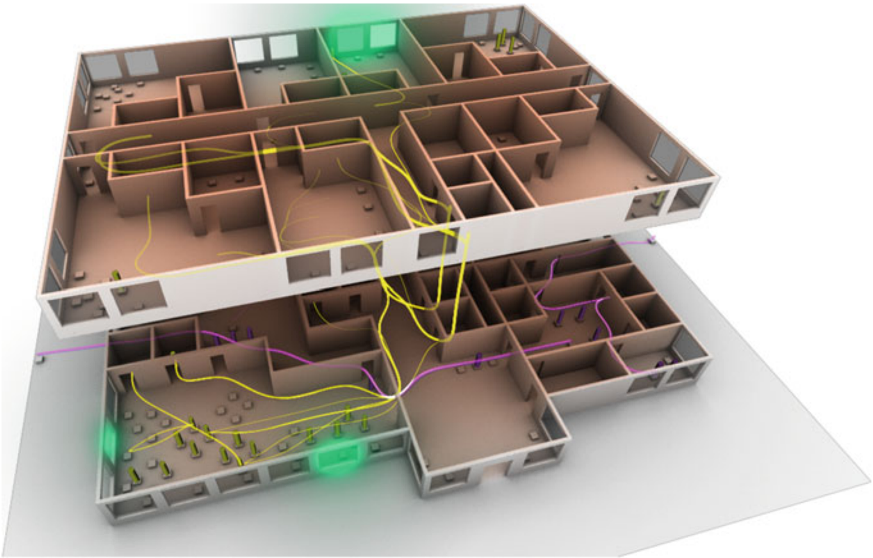

Fig. 8.9 Systems approach proof-of-concept modeled using DesignDEVS and visualized with Autodesk Maya

A key difference between dataflow programming and DEVS is that the latter allows cycles in the node graph. For example, if one of the inner system nodes in Fig. 8.8 represents a building's occupants, and another represents the building's indoor temperature distribution, the two-way relationship between human behavior and building thermodynamics can be established using links from each node to the other. The use of DEVS for this type of scenario was demonstrated by Goldstein et al. (2014) using DesignDEVS. New visualization techniques shown in Fig. 8.9 were researched by Breslav et al. (2014) to visualize the results. The speedlines in the figure animate the movements of a hotel's guests and employees, while glowing effects draw attention to the opening of windows by occupants seeking to improve their comfort level. The state of the windows affects the diffusion of heat through the building, shown as a color gradient on the floor. The indoor temperature then affects the likelihood of additional windows being opened.

The use of DEVS allowed the various simulation algorithms of the Fig. 8.9 model to be rapidly integrated, albeit by modelers with considerable experience with M&S techniques. Visual programming interfaces such as those in Fig. 8.8 may help introduce architectural researchers and building scientists to these scalable practices. Although the approach presented here could be used to model any real-world system, the popularity of dataflow programming among architects enhances its prospects in the realm of building design.

A systems approach offers a new way for researchers to collaborate in pursuit of next-generation simulation-based building design tools. It also represents a strategy for accommodating new design paradigms, in particular the emerging paradigm of

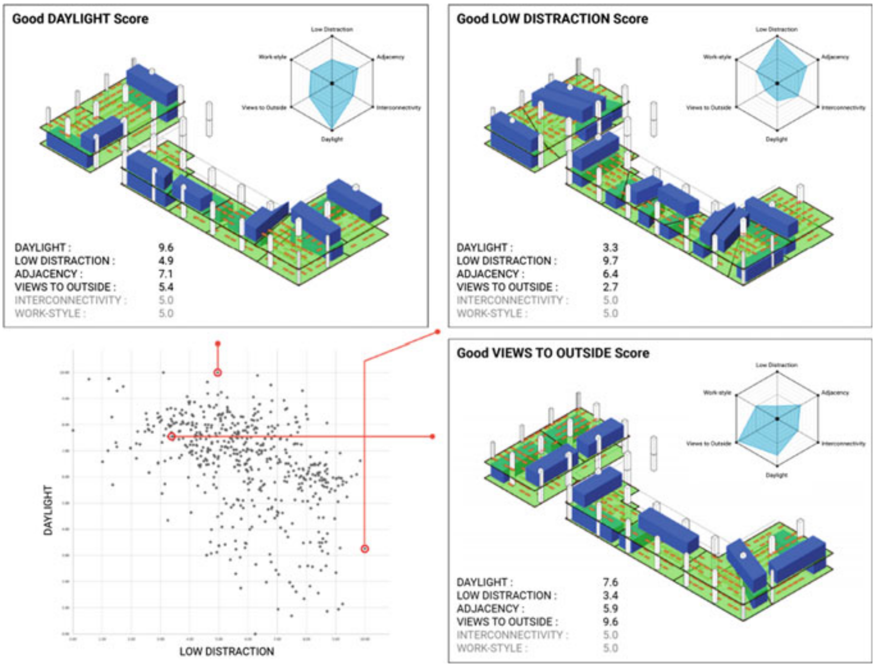

Fig. 8.10 Example of generative design for an actual office environment within the MaRS Discovery District in Toronto, Canada

generative design. Cloud computing and other technological developments have enabled computers to recommend plausible building geometries and systems configurations, primarily by generating and evaluating a myriad possibilities and automatically discarding poor performing options. Along with the closely related topic of multiobjective optimization (Keough and Benjamin 2010), generative design is receiving an increasing amount of attention among architectural researchers. Recently, the technique has been applied to the design of an office layout in order to satisfy several performance criteria including access to daylight, limited potential for distraction, and visual access to the building's surroundings. Figure 8.10 shows three generated layouts selected from a large sample of options.

The generative design project of Fig. 8.10 serves as an informative example for a number of reasons. First, it features geometric analyses that lend themselves well to dataflow programming, and will eventually need to be complemented with simulation. A systems approach combining dataflow with DEVS supports both the implemented analyses and the future simulation algorithms. Second, the results of the analyses are aggregated into a small number of performance metrics, which help inform the next iteration of generated layouts. The dataflow elements at the bottom right of Fig. 8.8 could provide a standard and scalable mechanism for deriving these performance metrics from geometric analyses and simulation results. Third, the project focuses on the experience of occupants in the built environment, a chief concern among architects that is not adequately addressed by current whole building energy modeling tools. Evidently, there is a need to provide architects with software that helps them satisfy objectives related to both human experience and sustainability.

8.5 Conclusion

When one considers the many processes and interactions that take place in and around buildings, as well as the extraordinary impact buildings have on the environment and on how people live their lives, the case for simulation in building design is obvious. Simulation is now heavily used by both architects and engineers in the AEC industry, for a variety of purposes including energy use prediction, structural analysis, and crowd planning. It is also actively researched, with occupant behavior and daylight simulation representing just two of the many current areas of interest. Yet the need for co-simulation developments such as the BCVTB—which is nevertheless an important, pioneering project—speaks to a legacy of large simulation codebases that were groundbreaking in their day but now limit the number of researchers who can effectively collaborate in the development of next-generation building design tools. Complex systems M&S ideas, particularly those that build upon dataflow programming and other techniques familiar to designers, may help architectural researchers and building scientists collaborate toward their common goal of creating more functional, sustainable, and compelling built environments.

Review Questions

1. Buildings account for approximately what percent of electricity use in the United States?
2. What is the difference between a building information model (Fig. 8.1) and an energy analytical model (Fig. 8.2)?
3. Which of these organizations/conferences—ACADIA, ASHRAE, CAAD Futures, IBPSA, Rob|Arch, SimAUD, Smartgeometry—focus primarily on (a) architecture, (b) engineering, (c) both disciplines?
4. What form of visual programming has recently become popular in the architectural design community?
5. The annual cost of heating and cooling a building is an example of a performance metric that could be used as part of a simulation-based architectural design workflow. What other performance metrics could be computed using simulation and applied to improve the design of a building?

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Author Biographies

Rhys Goldstein is a simulation expert in the Complex Systems group at Autodesk Research. His work straddles the disciplines of simulation theory and architectural design, and he has contributed as a researcher and conference organizer in both areas. Rhys and his colleagues received two overall Best Paper Awards: one at the 2010 IBPSA-USA Conference, for the customization of simulated human behavior in buildings; and one at SpringSim 2016, for a simulation development environment called DesignDEVS. Rhys served as the 2014 Co-Chair and 2015 Program Chair of the Simulation for Architecture and Urban Design (SimAUD) Symposium, and as Program Co-Chair of the 2017 TMS/DEVS Symposium. He is also an Associate Editor of the SIMULATION journal.

Azam Khan is Director, Complex Systems Research at Autodesk. He is the Founder of the Parametric Human Project Consortium, SimAUD: the Symposium on Simulation for Architecture and Urban Design, and the CHI Sustainability Community. He is also a Founding Member of the International Society for Human Simulation and has been the Velux Guest Professor at The Royal Danish Academy of Fine Arts, School of Architecture, at the Center for IT and Architecture (CITA) in Copenhagen, Denmark. Azam has published over 50 articles in simulation, human–computer interaction, architectural design, sensor networks, and sustainability. His Toronto team is currently developing a new experimental simulator to explore big simulation as a component of eScience, and his New York team, The Living, performs award winning design research in advanced architectural projects.