SimBuilding: Teaching Building Science with Simulation Games

"You can't have a high performance building without a high performance operator."
— National Energy Technician Education Summit: Summary, December 2010

Results from Prior Work

The Concord Consortium (CC) and Santa Fe Community College (SFCC) jointly propose this ATE project to systematically explore the potential of simulation games for improving the learning and teaching of building science and technology in community colleges. This proposal is based on the following prior work at each institution.

Prior Work at the Concord Consortium

The Engineering Energy Efficiency (EEE) project (http://energy.concord.org), funded by NSF's Discovery Research K-12 Program (DRL-0918449, $2.2M, 10/2009-9/2012, PI: Xie), has developed two innovative, open-source scientific simulation programs, *Energy2D* and *Energy3D*, to support STEM education related to energy concepts and applications. The project focused on educational research that aimed to provide insights on how high school students learn science and engineering with these simulation tools. Data collected from more than 600 students have revealed different learning patterns resulting from the affordances of these simulation tools, compared with traditional instruction and hands-on approaches. These simulation tools are beginning to have a broader impact in technical education. Since the release of its first beta version in 2011, *Energy2D* has been used by thousands of students and teachers around the world to learn and teach basic science concepts such as power, energy, temperature, solar radiation, and heat transfer. Through collaboration with Project Lead the Way, a leading provider of K-12 STEM curriculum, *Energy2D* is poised to reach thousands of schools. The research and supporting software developed in the EEE project provide the foundation for the proposed work.

The Concord Consortium also has a long history in developing and applying technology for embedded assessment (e.g., Horwitz, 2011) that is relevant to the proposed work. We have created a variety of logging systems that allow researchers and instructors to track students' learning progression with a piece of software. Several of our software products, such as the award-winning *Molecular Workbench* software (http://mw.concord.org) developed by the proposed PI at CC, support a form of intelligent tutoring (e.g., Koedinger & Aleven, 2007) that provides immediate and customized instruction and feedback to learners. These prior experiences will speed the development of a "smart" game-based learning system capable of detecting learner behavior and guiding their exploration, thus improving the outcomes of game-based learning and teaching.

Prior Work at Santa Fe Community College

The Center of Excellence for Green Building and Energy Efficiency and New Mexico Energy$mart Academy at SFCC (http://www.sfcc.edu/NM_energySmart_academy) are funded by the Department of Labor ($519,239, grant #12-631-9999-00036) and the Department of Energy ($423,849, grant #EE0004091). Under the direction of the proposed PI at SFCC, the Center is one of the country's 35 Weatherization Training Centers. It currently partners with Central New

Mexico Community College, Doña Ana Community College, Luna Community College, and the University of New Mexico, Valencia to conduct "train the trainer" events around the state. The Center has trained more than 300 students in the past eighteen months. To reach more students in New Mexico's rural communities, the Center is currently transforming its onsite courses into blended online courses that enable students to access the curriculum materials from their homes before going to the campus for face-to-face instruction and hands-on experiments.

Onsite programs are run through a state-of-the-art training facility. A fully equipped mobile training rig also takes training anywhere. Credit programs include Certificate and Associate Degree programs in Green Building Technologies, Energy Auditor, Solar Technicians, Biofuels, and Environmental Sustainability. Non-credit programs include Building Operator Certification, BPI and HERS Training, and Weatherization Training. SFCC is a BPI Test Center, a RESNET education provider, and a partner of the National Center for Healthy Housing and is applying for IREC accreditation for the non-credit weatherization programs. Nancy H. Sutley, Chair of the White House Council on Environmental Quality, praised the Center as "a great example of how communities are fulfilling President Obama's call for innovation and job creation."

The Need

As the building industry is adopting higher standards, technicians need to grasp a growing set of science concepts in order to understand and prevent building failures and optimize building performance. Technicians must know why they are doing things correctly or incorrectly, not just how to do them to meet a building code. In a recent ASHRAE Journal article (Lstiburek, 2012), the "Father of Building Science" Joseph Lstiburek described his frustration with International Energy Conservation Code (IECC) 402.6, which, under certain circumstances, imposes an incorrect configuration of floor insulation that compromises occupant comfort and energy efficiency. His story highlights the importance of "know-why." A good understanding of building science would have helped the LEED raters comprehend the issues better when an industry standard contains erroneous or contradictory instructions.

Not surprisingly, the Report of the 2010 National Energy Technician Education Summit also emphasized that foundational STEM skills are key technical skills for energy technicians (Advanced Technology Environmental and Energy Center, 2011). A solid STEM foundation enables technicians to learn new technologies, work in different sectors, and more effectively communicate with building scientists and engineers like Lstiburek. For example, heat transfer is a fundamental phenomenon that all building professionals must deal with (e.g., Harley, 2002). The thermal problems that an energy auditor, a building operator, or a weatherization worker encounters vary from one building to another and from commercial to residential, but they are all governed by the same set of basic concepts and principles of thermodynamics and heat transfer. The development of analytic and problem-solving skills in the field of green building rests on a firm understanding of these concepts and principles and, more importantly, the ability to apply them in order to reason about energy usage and flow in any building. However, in our experiences many students have poor understanding of heat transfer. Decades of educational research have shown that concepts about heat and temperature *per se* are notoriously difficult to students (Lewis & Linn, 1994; Sözbilir, 2003). Misconceptions such as "metals *are* colder than wood" are surprisingly strong and lasting, even after treatments with powerful technology-based interventions (Schönborn, Haglund, & Xie, 2013). These weaknesses in science could prevent students from attaining higher-level technical competency needed in a competitive job market. Worse, being academically unprepared could cause a large number of students to drop out from the field. According to the 2010 Survey of Student Engagement at SFCC, 42% students cited inadequate academic readiness as a main reason of attrition.

Many existing community college programs already provide excellent resources for teaching the "know-what" (facts) and "know-how" (procedures) required for green buildings. The "know-why" (science) part, however, is often more difficult to teach due to the lack of educational tools that can make building science concepts more accessible. For example, traditional methods for teaching thermodynamics and heat transfer inherit substantial formalism from academia. Such a formal treatment relies heavily on theoretical and mathematical analysis that is inappropriate at the introductory level. As a result, many building science concepts are simply taught to students as disparate facts and equations for them to memorize, without helping them to develop a coherent conceptual understanding. Community colleges need novel types of curriculum materials and instructions that can engage students in learning building science concepts more effectively.

Goal and Objectives

The goal of this project is to develop innovative simulation games for teaching and learning building science, integrate them into existing courses at SFCC, pilot test them in four community colleges in New Mexico, and evaluate their educational effectiveness through tracking and analyzing learner data. The project will accomplish this goal though the following objectives:

- **Develop a simulation game engine for learning and teaching building science**. The project will create a versatile and powerful simulation game engine, *SimBuilding*, which will support three types of simulation games—diagnostics games, construction games, and operation games—in both English and Spanish. These games will employ game mechanics similar to their entertainment counterparts, but each type will map to a cluster of building science concepts and practical skills related to real-world jobs such as weatherization workers, energy auditors, HVAC technicians, and building operators. For *SimBuilding* to be scientifically accurate and "smart," the project will develop an advanced multi-scale simulation method based on algorithms originated from the industry and academia for building design.
- **Integrate the game engine with a logging and tutoring system**. Learner data will be automatically logged and analyzed to record and reveal details about how the student learns through the games. Based on these details, an intelligent tutoring system will "coach" the learner. This computer-aided training system will also provide an open interface for instructors to customize or translate feedback to students to meet their own instructional needs.
- **Integrate games with existing courses**. *SimBuilding* games will be integrated into existing courses currently taught at SFCC and other partnering community colleges in New Mexico. Exemplary online curriculum modules using *SimBuilding* will be created using Google's *Course Builder* to take advantage of its capacity for large-scale cloud-based deployment. These modules will not only be integrated with SFCC's online programs, but will also be open to anyone interested in teaching and learning building science.
- **Conduct research and evaluation**. Pilot tests will be conducted with approximately 300 students in four community colleges in New Mexico through SFCC's Center of Excellence for Green Building and Energy Efficiency. Electronic data collected from these tests will be used to assess the degree of success of *SimBuilding* in education and training. Participating instructors will provide additional information about the transferability of game learning outcomes to job skills. Findings of this project will be presented at conferences and through pub-

lications. Independent of the research carried out by the CC-SFCC team, Sun Associates will evaluate this project formatively and summatively to provide an external perspective.

- **Disseminate the products**. *SimBuilding* games and associated curriculum modules will be disseminated through the Internet, including Google's *Course Builder* and the award-winning National Training and Education Resource (see Stubbs's letter from the National Institute of Building Sciences and Fox's letter from the Department of Energy). Through these efforts, we anticipate that *SimBuilding* will be used by a large number of students and eventually emerge as a viable, cost-effective solution to online green building education and training.
- **Reach out to high schools**. *SimBuilding* will also have the potential to engage precollege students to learn building science and develop an early interest in building careers. We will introduce *SimBuilding* to secondary teachers in New Mexico through free professional development workshops in hopes of catalyzing green building education at the grassroots level.

This project will be overseen by an outstanding Advisory Board consisting of industry leaders, education experts, and game developers (introduced later in the Personnel Section). They will bring their tremendous expertise and experience to ensure that this project will be on the right track to meet industry needs and standards and have broad impacts.

PROJECT RATIONALE

Building science is, to a large extent, a "black box" to many students, as it involves many invisible physical processes such as thermal radiation, heat transfer, air flow, and moisture transport that are hard to imagine. But students must learn how these processes occur and interact within a building in order to understand how design, construction, operation, and maintenance affect them and, therefore, the wellbeing of the entire building. These processes form a "science envelope" that is much more difficult to understand than the shape of the building envelope alone. With 3D graphics that can visualize these invisible processes in a virtual building, simulation games provide a promising key to open the black box. They offer a highly interactive learning environment in which STEM content and pedagogy can be embedded in the gameplay, game scores can be aligned to educational objectives to provide formative assessments, and students can be enticed to devote more time and explore more ramifications than didactic instruction. A significant advantage is that students can freely experiment with a virtual building to learn a concept before exploring it in a real building with all the consequences and costs that may entail.

Serious games and simulations have been widely used in education and training in other fields (Adams, 1998; Gee, 2007; Honey & Hilton, 2011; National Research Council, 2010), but their potential for teaching and learning building science and technology in community colleges has been relatively unexplored under NSF's ATE Program.[1] Despite the fact that there have been a number of commercial simulations developed by Interplay Energy (whose CEO is on our Advisory Board—see Donovan's letter) and several free ones offered by the National Training and Education Resource (NTER) portal,[2] there are three missing pieces:

- **An exposure to the "science envelope"**: Most existing games and simulations excel in training learners to complete a procedure ("know-how") but fall short of explaining the science

[1] An NSF award search using "game" as the keyword shows 11 ATE projects from 1997 to 2012. None of them is related to using simulation games to teach green building, energy efficiency, or renewable energy sources.
[2] See the Kuda Project used by NTER: http://code.google.com/p/kuda/

behind it ("know-why"). Science concepts pertinent to their training should be taught to students in the game world as appropriate. This requires simulation games to incorporate compelling, interactive scientific visualizations that can bring forward science concepts.

- **A way to evaluate learning**: Instructors and trainers need to have a reliable method to measure how students learn through gaming: Are they just playing or are they learning something? While simulation games have reportedly had varied degrees of success in other fields, their efficacy for green building training is yet to be confirmed. Such a study should use the data collected from students while they are playing with a game. Data-based evaluation technologies also have the potential to help training software developers improve their products.
- **A "smart" game to teach**: The power of a simulation game can be amplified if an intelligent tutoring system is incorporated to generate instant feedback to direct the gameplay based on learners' states and inputs (this technique is more generally known as "machine learning" in computer science). A modifiable tutoring system that can be customized by instructors to target their students' weaknesses would meet proven pedagogical needs.

Project Innovations

A critical innovation to support all these three missing pieces will be a powerful underlying science-based mathematical model that can accurately compute energy usage, heat transfer, and air/vapor/pollutant movement in virtual buildings, as well as the impact of the external environment such as solar radiation, rain, snow, and wind. Based on advanced building simulation methods (André, 2012; Clarke, 2001; Malkawi & Augenbroe, 2004; Woloszyn & Rode, 2008), this versatile mathematical model will be capable of simulating the energy and mass exchange across the building envelope, from which its hygrothermal performance can be evaluated. The calculated results will be used to create visually appealing, informative displays of the evolving systems in real time. These displays will show, for instance, temperature distributions similar to those generated by infrared thermography. Learners can tinker with the materials and designs of a virtual building to observe the effect of these changes on its energy consumption. For example, one can change orientation and glazing to compare different passive solar strategies. As the mathematical model of *SimBuilding* will comprise many variables and the variety of architectural designs is infinite, the opportunities for exploration and learning will be practically endless.

The power of a building simulation is not limited to rendering scientific visualization and supporting scientific inquiry. The calculated building performance data will provide a reliable method for generating game scores categorically, which can then be used to measure student performance. The scores can also be used to detect how far students are from the intended learning goals. These data can be fed to an intelligent tutoring system to guide students. This kind of computer-aided training system will be unique because it will incorporate the intelligence of building science simulation to assist the automatic assessment of learner performance.

The application of advanced building simulation technologies to developing training simulation games will be an original contribution of this project. Although building simulation has become an important tool in the industry[3] and can be very helpful in understanding how a building works

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[3] A complete list of building simulation software tools is available on the U.S. Department of Energy's website: http://apps1.eere.energy.gov/buildings/tools_directory/alpha_list.cfm. This collection represents decades of research in the building industry, worth billions of dollars of investment. The condensed wisdom can and should be used to build next generation training software that will be more rigorous, more interesting, and more powerful.

(Attiaa, Hensen, Beltránc, & Herdea, 2012; Mann, 2010), it has never been used to build simulation games before. *SimBuilding* will unveil this untapped instructional power.

Efficacy Study in New Mexico

The ability to measure student learning in simulation games makes it feasible to statistically gauge the efficacy of game-based learning. This is particularly important as many community college programs have incorporated a distance learning component to accommodate more students. Many online courses are being converted from “page turners” into interactive lessons. Because of their cost-effectiveness, simulation games represent one of the most promising learning technologies for realizing this upgrade (Stubbs, et al., 2012). A complete understanding of how they work in technical education will be needed to inform further investment and development. This project will conduct the first systematic evaluation of the extent to which the potential of simulation games can be fulfilled in a diverse setting. New Mexico, which has a large underrepresented population and a high poverty rate, will be a test bed for this evaluation. Among 6,519 students who have enrolled in the fall 2012 semester at SFCC, more than 60% are female and 46% identified themselves as Hispanic.

Technological Capacity of the Project Team

The proposers have more than a decade of experience in successful software development that has resulted in sustainable products used by numerous students. One of our energy-related products, *Energy2D*, is an easy-to-use interactive computational tool for modeling and visualizing energy transfer based on numerically solving basic physics equations such as the heat equation and Navier-Stokes equation (Xie, 2012a). Students can use it to explore heat and mass flows in 2D structures under different environmental conditions such as sunlight and wind (Figure 1a). Virtual sensors, including thermometers, anemometers, and heat flux sensors, are available for quantitative analysis. These sensors can be connected to virtual controllers such as thermostats to create virtual engineering systems (Figure 1b).

Another program, *Energy3D*, is a computer-aided design and digital fabrication tool based on a game engine called *Ardor3D*. This educational tool supports the full-cycle technology learning experience: Students design a building on the computer, evaluate its energy performance using the built-in analytic tools, and print and assemble a physical model for follow-up tests in the real world. The program also provides a virtual heliodon for examining solar heating on the building under design for any selected location on the planet (Figure 1c). Virtual HVAC components can be set up in the building (Figure 1d).

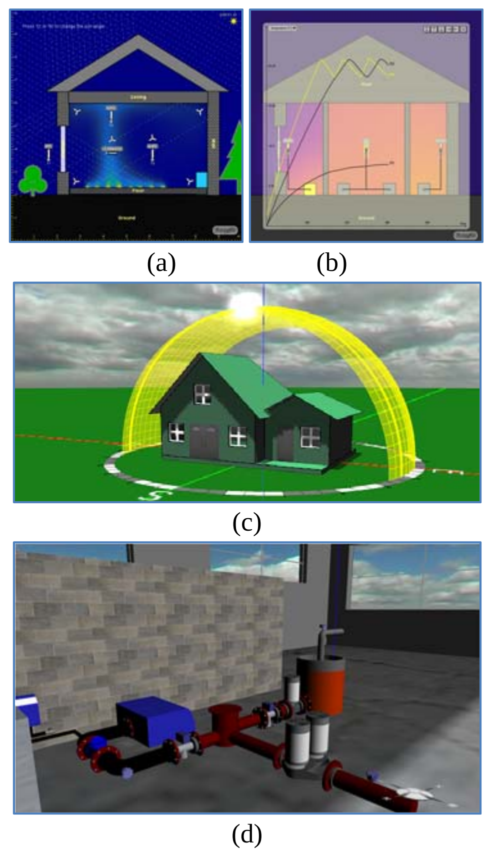

Figure 1. (a) An Energy2D simulation of natural convection in a house due to solar heating through a glass window. (b) An Energy2D simulation of the duty cycles of multiple heaters controlled by multiple thermostats. (c) The virtual heliodon in Energy3D. (d) HVAC components in Energy3D.

In addition to our in-house expertise in building physics, computer simulation, and software development, two distinguished scientists Drs. Joseph Lstiburek and John Straube from Building Science Corporation (http://www.buildingscience.com) will serve as consultants to provide further scientific and engineering support (see the letter from BSC's President Betsy Pettit).

TECHNOLOGY DEVELOPMENT PLAN

SimBuilding will combine a building simulation engine with elements of gameplay, education, and evaluation (Figure 2): 3D graphics will render realistic building look and feel; ongoing challenges will keep the learner engaged; every player will have a chance to succeed; different game levels will scaffold a learning progression; and just-in-time instruction will coach the learner. The game engine will be based on WebGL, which is a JavaScript application programming interface to OpenGL for rendering interactive 3D graphics within any compatible web browser without the use of a plug-in. Built in WebGL, *SimBuilding* will run on any smartphone, tablet, or regular computer, making it widely accessible.

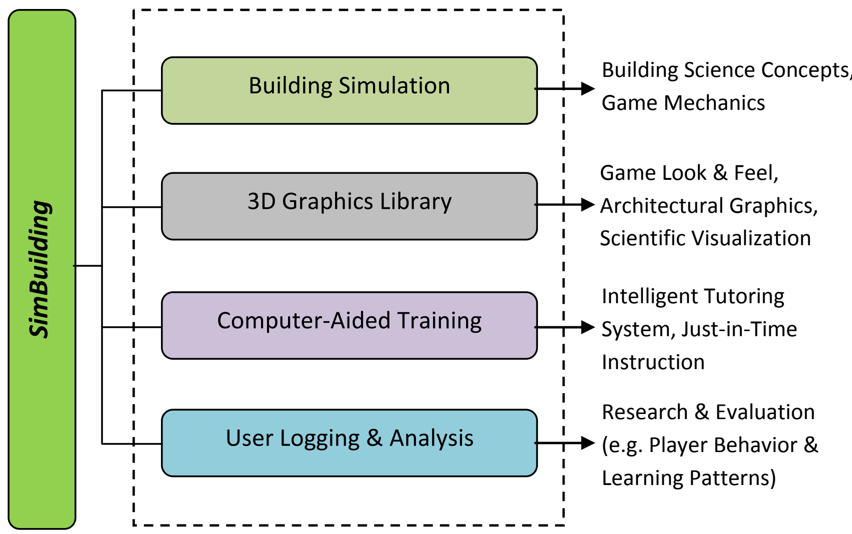

Figure 2. The four modules of SimBuilding and their corresponding functions.

It is important to emphasize the difference between building simulation and heat load calculation. Many HVAC technicians use an online heat load calculator to determine the power of a heating or cooling system required for a building. In such a calculator, students can plug some values in a Web form and get a result in BTU or kilowatts instantaneously, without knowing exactly where and how heat is gained or lost. To be more educationally useful, the *SimBuilding* engine will be much more sophisticated, comprehensive, and descriptive than a heat load calculator. Buildings are large complex systems that contain countless details across scales from millimeters to decameters. Students not only need to understand buildings as systems but also the constituent elements as interdependent operational units. To create a holistic learning experience, the simulations of systems and components must be integrated in a single environment. A key innovation of this project will be a multi-scale building simulation engine.

- **System ("Macro") Simulation:** At this level, the entire building will be modeled as a network of interconnected nodes, each representing a component such as a zone, a wall, a window, an HVAC unit, a renewable energy system, or a climate condition. These nodes interact with one another through the exchange of heat and fluid (air and vapor), the rate of which is determined by thermostats, fans, ducts, relative humidity, dew point, outdoor climate, infiltration, and other mechanisms that can cause temperature, concentration, or pressure gradients. The dynamics of the building is then simulated by solving the group of differential equations that link all these variables together, subject to the conservation of energy and mass and the requirements to maintain indoor quality. The total energy consumption is computed by summing up the inputs. The nodes are associated with visual components in the virtual building such that any modification of the building on the screen by the player, such as adjusting the insulation level of a wall from R5 to R11, will vary the node(s) beneath the modified part and immediately lead to changes of inputs and/or outputs across the network. Arrows that represent the flow paths of air, heat, and vapor will be rendered in the 3D scene to visualize those changes. For example, replacing a single-pane window with an energy-efficient one will cause the corresponding nodal properties (e.g., the R-value and glazing) to change, which subsequently shrinks the heat flux vector perpendicular to the window that represents the energy loss through it. The nodal network will also respond to dynamic changes such as certain weather condition or HVAC malfunctioning that lasts for an indefinite amount of time. This will be important for implementing the game dynamics through which the player will be constantly challenged with randomized onsets of simulated problems.

- **Point-of-Interest ("Micro") Simulation**: Physical processes are often modeled using a finite difference or finite element method that divides the volume of a building component into many small grid cells, linked by fundamental equations in physics that govern heat transfer and fluid flow. Recognizing that such a fine-grain simulation (often known as computational fluid dynamics by building scientists) for the entire building is too time-consuming to be practical in a simulation game, we will implement a partial solution that allows the user to pick a point of interest and "zoom" into it. An enlarged view of a small volume (or simply a 2D area or cross-section) containing the point will appear on the screen (Figure 3). A "micro" simulation will be performed to show the details of the physical processes within the selected area or volume. For example, when the learner clicks on a wall, such a simulation can be brought up to show if a convective air loop may form inside a wall cavity to accelerate heat loss (Sidall, 2009). The learner can close a gap or insert an obstruction to explore if the air loop can be stopped or disrupted. A "micro" simulation can even go down to the molecular level to show, for example, how a water molecule travels through different "maze-like" building materials through diffusion or capillary conduction, or condenses onto a cold surface it encounters inside a wall assembly. This kind of molecular simulation game will help students understand the atomic-scale mechanisms responsible for vapor transport, dew point, etc. and explore strategies to control the moisture accumulation in the building envelope (e.g., installing vapor diffusion retarders). This development will leverage our expertise in interactive molecular simulation (Xie, et al., 2011).

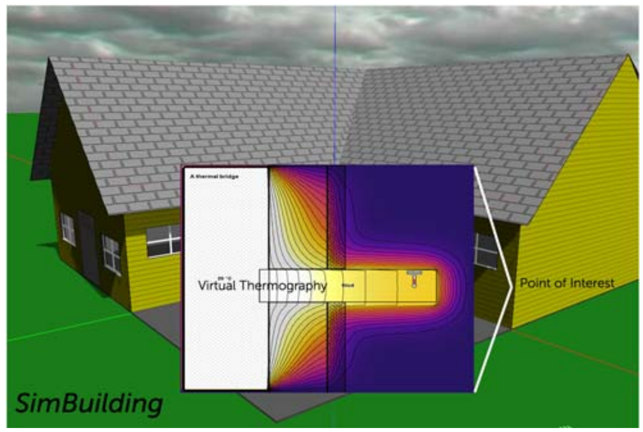

Figure 3. An illustration of "zooming" into a point of interest in SimBuilding to observe and interact with a fine-grain simulation of the cross-section of a thermal bridge that renders a virtual thermogram, which uses the "Iron" coloring similar to the corresponding coloring mode used in FLIR's infrared cameras.

- **Coupling of "Micro-Macro" Simulations**: Following published computational methods (e.g., Djunaedy, Hensen, & Loomans, 2005; Zhai & Chen, 2005), the "macro" and "micro" simulations described above will be coupled so that students can observe how changes at one level affect properties at the other. To couple them, the boundary conditions and initial conditions of a "micro" simulation will be derived from the time-varying properties of the "macro" nodes that are associated with the selected "micro" volume or area, calculated by the "macro" simulation for the whole building. Conversely, modifications of the elements in a "micro" simulation (such as adding or removing an air barrier or a vapor retarder in a wall assembly) will affect the properties of the associated "macro" nodes and impact the performance of the entire building through the system dynamics. In this way, the two levels of simulation can be intimately connected to render a complete picture of the building physics.

Note that the proposed computational capacity of *SimBuilding* will make it possible to teach a critical technical skill—data collection and analysis—through a simulation game. This skill is difficult to teach in the classroom or in an online course, as many data collection processes in real buildings are too time-consuming to show in real time. But *SimBuilding* will be able to rapidly generate data of arbitrary time length resembling real-world data for any condition students set up in a virtual building, enabling students to practice this skill efficiently.

The logging system to monitor student interactions in *SimBuilding* and the tutoring system to provide just-in-time instruction and computer-aided training will utilize existing software systems developed at CC through other projects (e.g., *Simulations for Performance Assessments that Report on Knowledge and Skills*, http://concord.org/projects/sparks). As *SimBuilding* will be deployed through Google's *Course Builder* for massive open online courses (MOOCs), we will also investigate the feasibility of using Google Analytics to track student learning with *SimBuilding* in a MOOC environment. This will enable the entire *SimBuilding* platform to run in the cloud, making it capable of serving a large number of students in the future.

TYPES OF SIMBUILDING GAMES AND THEIR MECHANICS

SimBuilding will support three types of simulation games that differ in the game mechanics:

Diagnostics Games

A diagnostic game will be a first-person game that trains technicians in energy auditing, quality assurance, moisture control, and so on. Similar to treasure hunt games, building diagnostics can be regarded as a kind of "fault hunt" game, in which learners are given a variety of analytic tools to identify problems in a virtual building. The virtual diagnostic tools will include simulated versions of data loggers, infrared cameras, and blower doors with manometers to inform the learner with calculated data from the building simulation. The player can place a virtual data logger anywhere in the virtual building to monitor temperature, heat flux, relative humidity, or pollutant level. A virtual infrared camera can provide a simulated thermal vision in a selected viewport (Figure 3 inset). A virtual blower door can be used to alter the pressure difference between the inside and outside of a house to create a simulated situation in which defects in the air barrier can be detected. A virtual atomic microscope can zoom into the molecular world inside a construction material to show a nanoscale picture of what is going on. *SimBuilding* will provide simulations of both good and bad conditions to test the learner's ability to distinguish them based on virtual data collection and analysis. For example, an instructor can deliberately set up a condition in which the insulation of a wall is compromised by a steel stud that acts as a thermal bridge. The learner is then challenged to sort it out using a diagnostic tool. Game scores will be calculated based on the number of faults the learner finds and the correct items the learner selects in the diagnosis report. The learner will win the game if all the faults are identified and reported within a given amount of time. Just like in any other game, the learner can always try again if she fails. When the learner wins, the reward will be a new, larger "contract" that brings her to the next level. Scenarios of the diagnostics games will be drawn from real-world cases, such as those identified in the *Thermal Bypass Checklist Guide* (Energy Star, 2008).

Construction Games

A construction game will teach fundamental building science concepts through virtual construction, retrofit, and commissioning. Students will be challenged to create a virtual green building from scratch or remodel an existing building to meet energy efficiency standards, livability requirements, environmental goals, and budgetary constraints. A rich set of 3D objects that represent a variety of constructional and HVAC units (Figure 1d) will be provided for students to quickly drag and drop into the scene to assemble or modify a building (or a part of it, such as in a challenge to build a perfect wall or roof by choosing different materials and stacking them up). The game can calculate—in real time, while the player is constructing—a set of scores in terms of material cost, energy consumption, and carbon footprint to show the "greenness" of a building being constructed or remodeled, which drives the gameplay. To keep the game constantly challenging, there will be an accompanying commissioning or retrocommissioning simulation as students complete their construction or retrofit projects for verifying the building performance in a selected climate. This "commissioning" process will be based on virtual diagnostic and functional tests powered by *SimBuilding*'s computational engine. Test results will reveal problems in students' constructions and spur them to realize mistakes and correct misconceptions (which, in turn, will teach them some basic knowledge needed to become a building commissioner). For example, the temperatures in different heating zones will indicate if the heat load is calculated correctly and distributed properly. Students can revisit the design and redo those parts of the building until it passes the test. The iteration of this regulated learning process can help students learn progressively towards an integrated understanding of building science. Contemporary concepts and technologies, such as passive house (Klingenberg, Kernagis, & James, 2009) and moisture buffering (Rode & Grau, 2008), will also be infused through the gameplay.

Operation Games

An operation game will train building operators and managers. In such a game, learners operate or manage virtual buildings with limited resources to meet a comfort level for occupants. Running a building is not the job it used to be. The complexities and interdependencies of a facility's systems–HVAC, electric, lighting, etc.–require an understanding of the big picture to ensure that all subsystems are put to work together optimally to achieve greater energy efficiency and comfort level. Considering that many buildings are adopting computer-controlled building management systems (BMSs), *SimBuilding* operation games will familiarize students with a virtual BMS. *SimBuilding* will emulate the four basic functions of a BMS: controlling, monitoring, optimizing, and reporting, with a focus on energy consumption. All these functions will be connected through artificial data computed by *SimBuilding* and displayed by the simulated monitoring systems (such as a virtual control panel connected to virtual sensors that monitor the indoor air quality). As *SimBuilding* can evaluate the building performance, students will be able to quickly test an optimization measure with a virtual building. Another important part of the operation games will be a dynamic situation simulator, which creates a set of parameters that defines a situation (e.g., the complaint from an occupant due to an HVAC breakdown or a smell of mold).

These parameters are then fed to *SimBuilding*'s computational engine to produce and report abnormal data that challenge learners to track down the causes and find a solution.

Curricular Integration

SimBuilding games will be integrated with existing courses at SFCC. Because of its deep roots in building science, *SimBuilding*'s simulation engine will provide a natural platform for supporting the course content. For example, the nodal network method for the system dynamics simulation described earlier fits the introductory course "House as a System" well. By playing with *SimBuilding*, students can develop an intuitive understanding that the performance of a building depends on the performance of all of its subsystems, each of which contributes in a unique but interdependent way. *SimBuilding* will be able to demonstrate that one subsystem can deceptively cause a symptom of another via interactions defined in the nodal network. Properly diagnosing and fixing the real culprit requires an analysis of these interactions, which can be taught by visualizing them through the nodal network simulation.

We plan to upgrade SFCC's online modules using Google's *Course Builder* and embed these games into the new modules. These modules will be designed as short courses, but can be remixed to create a longer course. The modules will support the following courses: A) House as a System, B) Efficient Envelopes, C) Green Building, D) Residential Diagnostic Testing, E) Energy Auditor, F) Retrofit Weatherization Technician, G) Crew Leader, H) Quality Control Inspector, I) BPI Building Analyst, J) RESNET HERS Rater, K) Green Construction Skills, and L) Building Operator Certificate. Some of the proposed games, such as the diagnostics games, will be used across multiple courses. Instructors will be able to customize them, for example, by selecting particular topics and levels.

Dissemination

SimBuilding will be open-source and freely available on the Internet. The simulation games and curriculum materials based on them will be shared with other community colleges through collaboration. In addition, we plan for the following dissemination opportunities: 1) free summer professional development workshops for high school teachers and community college instructors in New Mexico; 2) Apple Store and Google Play; 3) the National Training and Education Resource that will train thousands of green building workers in a decade (see Fox and Stubbs's letters); and 4) professional conferences and publications.

Research and Evaluation

The research and evaluation of this project will include an internal part and an external part. The internal research, which will be carried out by the CC-SFCC team, will focus on studying the efficacy of *SimBuilding* games for technician education. The external evaluation, which will be independently conducted by Sun Associates (http://www.sun-associates.com), will focus on gauging how the project operates to meet the goal and objectives defined in this proposal.

Internal Research

The internal research will be based on pilot tests planned at four participating community colleges in New Mexico: SFCC, Central New Mexico Community College, Doña Ana Community

College, and Luna Community College. About 300 students will be involved in the pilot tests and their feedback will be used to improve *SimBuilding* for large-scale applications.

The research will be concerned with two questions: 1) what students learn from *SimBuilding* games and how their learning outcomes can be enhanced; and 2) how well their learning can be transferred into job skills. The answer to the first question will be based on analyzing the electronic data collected through the logging system. The answer to the second question will rely on the instructors' assessments, with a focus on the degree to which students' scientific reasoning ability for solving real-world building problems has improved. SFCC student records and class evaluations from prior years will be used as the baseline data source to evaluate improvements due to the use of *SimBuilding* in the courses. The applications in a real classroom and in an online course will be compared to evaluate its relative effectiveness between a formal and an informal implementation. We will also examine if the use of the simulation games can play a positive role in engaging more students to study building science. This may be measured by comparing the numbers of student enrollment before and after *SimBuilding* is introduced in the curriculum and by calculating the percentage of students who enroll in a degree or certificate program among the registered game players. Research on these questions will be condensed into recommendations about the best instructional strategies for using *SimBuilding*.

External Evaluation

The external evaluation will follow the guidelines of the Evaluation Resource Center for ATE (http://www.evalu-ate.org). Summatively, the evaluator will observe activities and document outputs and outcomes. Formatively, the evaluator will monitor project progress and will provide project staff with inputs on improving their work to ensure positive outcomes. The evaluation will focus around two primary questions: 1) To what extent have *SimBuilding* games and curricula engaged students to learn building science and assist community college instructors to teach building science? 2) To what extent has the project contributed to green building technician education programs through the proposed activities in New Mexico and the country at large?

In order to conduct this evaluation, the evaluator will engage in a number of specific avenues of investigation. The highlights of these are as follows:

A. **Creation of benchmarked performance indicators for overall project assessment**. At the beginning of the project, the external evaluator will work with project staff, the Advisory Board, and the participating faculty to develop a benchmarked set of project performance indicators based on the two evaluation questions above and the project goal. Arranged into a rubric, the indicators will provide clear criteria for project success (summative evaluation) and benchmarks used throughout the three project years to show how the project qualitatively and quantitatively improves its performance (formative evaluation).
B. **Assessment of the community college implementations**. Utilizing the content expertise of the Advisory Board, the evaluator will evaluate the quality of the *SimBuilding* games and the associated curriculum units as well as how these materials are implemented online and onsite. The evaluator will develop an indicator rubric that assesses the connection between the materials and how they attract and retain students and help them develop real-world job skills. The faculty at the four participating community colleges will also provide inputs for evaluating the effects of the simulation games based on their experiences in using them with

their students. A number of research instruments including embedded assessments, questionnaires, and interviews will be used to collect student opinions about the games.

C. **Assessment of dissemination and industry approval**. The evaluation will not only measure the number of people impacted by each of the dissemination means, but will also collect and summarize reviews by the Advisory Board, the consultants from the Building Science Corporation, and the participating instructors for use as a measurement of industry acceptance of the project's products and outcomes.

In addition to regular formative reporting to the project staff, the external evaluator will report summatively via an annual report submitted to the project, its advisors, and the NSF. The report will also include recommendations for improvements.

SUSTAINABILITY PLAN

As with other software tools created by the proposers, *SimBuilding* will continue to be developed, maintained, and promoted after the completion of this project. Its website will continue to be in service for the public. As it matures, future versions of *SimBuilding* games may be commercialized to meet the growing needs of green building training. After the usage reaches a critical mass, game objects can be "adopted" by the industry for a fee: a game object can bear a manufacturer's brand name, mimic its look, and import its specifications to advertise for the sponsor.

PROJECT SCHEDULE AND MANAGEMENT

This three-year project is scheduled as follows:

- **July 1, 2013-June 30, 2014**: The project will focus on developing the *SimBuilding* game engine in the first year. An outline of integration with existing curriculum materials will be developed simultaneously to guide the software development. Most materials will be deployed online using Google's *Course Builder*. By the end of this year, an alpha version of the game engine will be ready for pilot tests. The advisors will meet at the end of this project year.
- **July 1, 2014-June 30, 2015**: Phase One Pilot Tests of *SimBuilding* games, integrated with existing courses and lesson plans, will be conducted with 100 community college students. These tests will provide first-hand user data and instructor feedback to help the project improve the game engine and the materials. Electronic data will be collected to test the reliability of the logging and tutoring systems. The first statewide workshop will be provided to community college instructors and high school teachers. The second Advisory Board meeting will be held at the end of this year to review the pilot test results and give further suggestions.
- **July 1, 2015-June 30, 2016**: Phase Two Pilot Tests will be conducted with 200 students throughout the year. More curriculum units will use *SimBuilding* games, some customized by the course instructors. Electronic data will be collected and analyzed to reveal learning patterns of students using these games. The beta versions of the games will be available to the public through the Internet and will also be disseminated through partners. The project team will present products and results through conference presentations and journal publications.

PERSONNEL

The Advisory Board

An Advisory Board will oversee this project and help it achieve its goal. The advisors will meet with the staff twice to review the products, the evaluation results, and the dissemination efforts.

They will compile a report after each meeting that will include recommendations addressed to the staff and forwarded to the cognizant program officer. The advisors are:

- **Dr. Douglas Clark** is Associate Professor of the Learning Sciences and Science Education at Vanderbilt University. His research focuses on students' learning processes in the game-based environments. He will advise us on game-based strategies for learning science.
- **Doug Donovan** is CEO of Interplay Energy, which develops 3D interactive simulation training and testing applications for the clean energy workforce. He will help *SimBuilding* meet the standards of the corporate training market for building science.
- **Roger Ebbage** is the Energy Management Program Manager at Lane Community College. He was recently selected as the "Energy Manager of the Year" by the National Association of Professional Energy Managers and "Innovator of the Year" by the Community College League for Innovation. He will advise on collaboration with other community colleges.
- **Steve Hale** is the Program Director of Build Green New Mexico (BGNM). BGNM is a statewide program for certifying green residential buildings and encouraging homebuilders to use technologies, products, and practices that will provide greater energy efficiency. He will help *SimBuilding* become a useful training tool for New Mexico's green workforce.
- **Craig Savage** is Co-President of Building Media, Inc. He has 25 years of service in the construction industry as a building contractor, remodeler, and custom homebuilder. He will bring strategies for integrating *SimBuilding* with online learning that he has spearheaded.
- **Stephanie Stubbs** is the Program Director of the Building Enclosure Technology and Environment Council at the National Institute of Building Sciences. She will share with us her experience with NTER and help us disseminate *SimBuilding* through the portal.
- **Nicole Yankelovich** is the Executive Director of the Open Wonderland Foundation and CEO of WonderBuilders, which creates custom virtual worlds for clients. She directed many projects in Sun Microsystems Laboratories before founding Open Wonderland. She will be our technology advisor for virtual world development and integration.

Staff at the Concord Consortium

- **Dr. Charles Xie** will serve as the Principal Investigator at CC. Charles has taught himself building science and technology, especially building simulation, in the past four years. A computational physicist by training, he has developed innovative energy simulation software for education (*Energy2D*). He is also expert in infrared thermography (Schönborn, et al., 2013; Xie, 2011, 2012b; Xie & Hazzard, 2011) and was a keynote speaker at InfraMation 2012—the world's largest conference for infrared thermography. His molecular simulation work, the *Molecular Workbench* software, has reached nearly a million users worldwide and won a prestigious *Science* Prize for Online Resources in Education (SPORE) awarded by Science Magazine. Charles holds a Ph.D. in materials science and engineering from the University of Science and Technology, Beijing. In addition to leading this project, he will develop the building simulation engine for *SimBuilding*, as well as the game mechanics.
- **Dr. Saeid Nourian** will be a senior software developer, responsible for developing the game effects of *SimBuilding* and integrating *SimBuilding* with a logging system and an intelligent tutoring system. His past research includes a collaborative cataract eye surgery simulation that allows instructors to mentor students during a virtual cataract surgery. He is also the architect of a generic framework that makes it possible to integrate discrete computational and visual components together in order to create a wide range of configurable biological simula-

tions. He is the developer of *Energy3D*, as well as the world's best 3D Graphing Calculator. Saeid holds a Ph.D. in computer science from the University of Ottawa.

- **Edmund Hazzard** will be the senior curriculum developer, responsible for integrating the games with existing curriculum materials. A practicing builder and architect for 30 years, he has acquired a comprehensive knowledge of energy conservation, solar design principles, and construction details. He holds a B.S. in physics from Haverford College, a Master's Degree in Architecture from the University of California, Berkeley, and a Master's Degree in Teaching from Tufts University.

Staff at Santa Fe Community College

- **Amanda Evans** will serve as the Principal Investigator at SFCC and will manage this project. She is Director of the Center of Excellence for Green Building and Energy Efficiency and the Project Manager of the New Mexico Energy$mart Academy at SFCC. She teaches the BPI Building Analyst and Envelope Professional certifications, the RESNET HERS certification and other courses in the NME$A program. She is on the Board of the Santa Fe Area Homebuilders' Association, U.S. Green Building Council in New Mexico, Foundation for Building, National Energy Educators Institute, and the U.S. Department of Energy Weatherization Plus Committee. Amanda was a panelist at the MIT "Women in Clean Energy Symposium" and was invited to discuss weatherization issues at the White House.
- **Jeff Granger** will be a senior instructor and researcher for this project. He began his energy-training career in 1979 while working for a home building school and energy software developer, the Cornerstones Energy Group. He taught energy auditors throughout New England, in Pennsylvania, and in California. Today, he teaches at the New Mexico Energy$mart Academy and in the PV Academy and Weatherization Technician programs at Central New Mexico Community College in Albuquerque. He is a volunteer at the New Mexico Chapter of the Green Building Council and the New Mexico Solar Energy Association.

Consultants at Building Science Corporation

We are fortunate to have two world-class building scientists as consultants to ensure the integrity of the building science to be built and delivered in *SimBuilding*.

- **Dr. Joseph Lstiburek** is a forensic engineer who investigates building failures. His authority on moisture-related building problems and indoor air quality is internationally recognized. His work has influenced building codes and standards in every climate zone. EcoHome magazine called him the "Father of Building Science," and Fast Company magazine referred to him as "the Sherlock Holmes of Construction." The Wall Street Journal states he is widely recognized as "the Dean of North American Building Science."
- **Dr. John Straube** is a specialist building science engineer who has been deeply involved in the areas of building enclosure design, moisture physics, and whole building performance as a consultant, researcher, and educator. He is also a faculty member in the Department of Civil Engineering and the School of Architecture at the University of Waterloo where he teaches courses in structural design, materials science, and building science to both disciplines.

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