Int. J. Engng Ed. Vol. 24, No. 3, pp. 521–528, 2008
Printed in Great Britain.
0949-149X/91 $3.00+0.00

Using the Technology of University Buildings in Engineering Education*

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The Faculty of Applied Science at Queen's University has introduced an integrated and comprehensive approach to engineering education called Integrated Learning. In order to support this program, a new building, Beamish-Munro Hall, has been constructed to provide multidisciplinary plazas and innovative teaching studios as well as supporting facilities for team-based, project-based learning. One element of the plan has been the use of the technology inherent in the building itself to support the educational program. We call this aspect of the program 'the live building'. This paper describes the construction, development and operation of the live building elements chosen; the problems encountered; and some preliminary results.

Keywords: active learning; project-based learning; live building; building technology; building systems; sustainable building; interactive website

BACKGROUND

THE FACULTY OF APPLIED SCIENCE at Queen's University recently introduced an approach to engineering education called Integrated Learning [1–3], affecting all engineering programs within the Faculty of Applied Science. Its objectives are:

- to increase the proportion of learning that is active rather than passive;
- to increase the professional skills of engineering students;
- to enhance student understanding of the impact of engineering on the economy, on the environment, and on society in general and hence of the necessary impact of economic, environmental and social considerations on engineering design;
- to increase the quantity of design education;
- to increase the appreciation that each engineering student has of other engineering disciplines and, indeed, of other disciplines in general.

In order to achieve these objectives, we needed to increase our use of techniques that supported them, such as the adoption of team-based, project-based learning in year one, the increased use of project-based learning in other years, the introduction of studio methods and the creation of courses in collaborative, interdisciplinary design. The existing facilities of the university, while more than adequate for traditional approaches to education, were either inadequate or lacking altogether with regard to the increased use of active learning techniques. In order to obtain suitable facilities, a new building was created, Beamish-Munro Hall, which opened in 2004. It contains:

- forty-two group rooms (student-bookable work spaces for groups and teams);
- a first year studio;
- plazas (open laboratory areas supporting simultaneous activities of students in different disciplines and years) ;
- a Site Investigation Facility;
- an experimental Teaching Studio;
- an experimental Active Learning Centre;
- a multidisciplinary Design Studio and a Prototyping Centre;
- a multimedia centre; and
- facilities for competitive design teams.

In order to obtain the maximum educational value from the new building, three guiding principles were adopted during the design stage.

The first principle was to use the building's structure and equipment to provide as many learning opportunities as possible. In some cases, this simply involves exposing features that would normally be concealed. In others, it involves monitoring the building's operating systems and putting the data online for use in classes, in projects, or for personal interest. This allows students to see how building operation changes in response to occupancy, time of day, time of year, weather and so on. This is live building [3], and the subject of this paper.

Secondly, since we all learn outside of the classroom as well as inside, it was and is important that the social and environmental lessons learned in observing what happens in the building be appropriate and of the highest standard.

Finally, the building had to be attractive to students. Students were consulted in many ways from the very beginning, and the architects gave great attention to making the inside environment both supportive and exciting. We want students to want to spend time there, and they do. The organ-

* Accepted 18 June 2007.

ization representing all undergraduate engineering students at Queen's, the Engineering Society, has its offices just inside the main door. The building is open long hours, seven days a week.

THE ROLE OF 'LIVE BUILDING'

The idea of using a building's own features as part of engineering education, or indeed as part of education generally, is not new. For example, various energy-efficient buildings have been built throughout the world and their innovative elements monitored in order to contribute to public education. The ITLL at the University of Colorado at Boulder, which was in various ways a model for Beamish-Munro Hall, used several opportunities to expose building techniques and to monitor performance [4].

Beamish-Munro Hall differs from most other buildings in that its design sometimes takes a different form from what would emerge if one were not serving the pedagogical goals of live building. For example, the office wing at the west end of the building is a steel structure whereas the main body of the building is a concrete structure. Normally, one or the other would have been chosen for the whole building. Here, both were used so that students could compare the two. Similarly, on one section of the office block, twelve different glazings are used so that students can compare their optical and thermal performance over time and under varying conditions. This is an example of where our desire to produce engineers who are environmentally aware took precedence over our desire to have the best possible building from an environmental viewpoint.

The Live Building concept contributes directly to increasing the proportion of learning that is active rather than passive, especially through the opportunities for meaningful projects at every level. It also contributes significantly to increasing student knowledge of other engineering disciplines. For example, reinforcing bars are exposed—and explained—in three different contexts: in a shear wall, in a column, and in a floor. Any electrical or mechanical or chemical engineer with curiosity picks up a little bit of awareness of how reinforced concrete structures are built. If he or she has sufficient interest, the entire building process was recorded and can be studied. Not all students will be interested, but the facilities pique the curiosity of some, and the opportunity to satisfy that curiosity is there. Finally, the live building concept also contributes to our other guiding principles. It is the live building features, for example, that make the green building features evident. And live building has certainly played a role in making the building interesting to students.

THE MAJOR FEATURES OF THE LIVE BUILDING

The live building consists of exposed elements, educational displays, and thousands of data points from data acquisition systems throughout Beamish-Munro Hall and across the Queen's campus. The live building may be viewed as an integrated whole because, by dint of significant effort and the

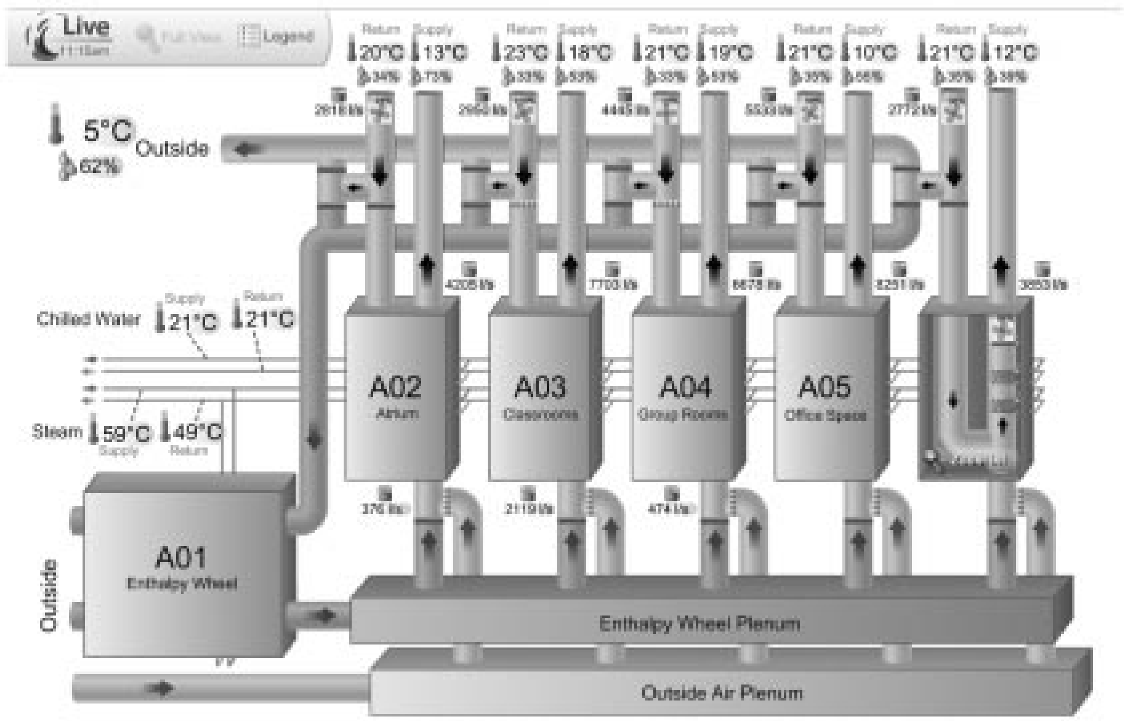

Fig. 1. Real-time Flash display of the HVAC system.

cooperation of many vendors, the various systems are all accessible through a single database front-end. The various components are in fact quite distinct and of many types, as described below.

The heating, ventilation and air conditioning (HVAC) system

Most of the live building measurement points—over four thousand of them—are in the HVAC system. The data from the sensors required for control of the heating, ventilation and air conditioning equipment are available online for use in academic programs. Interactive, real-time displays on the website demonstrate the operation of the air-handling units. (See Fig. 1.)

The hallways and some office spaces have no ceilings so that many components of the building systems are visible, including pipes, valves, actuators and sensors. The building's penthouse was made large enough to accommodate guided tours, so that groups can see the sensors, microprocessors, actuators and other aspects of the HVAC system.

Continuous monitoring of the HVAC system has had implications for building commissioning and management. Graphs of the numerous measurements make problems with the system more evident. This creates the potential for the building to be 'continuously commissioned', a process that has been shown to be capable of saving between 15 and 30% on energy costs by correcting inefficiencies [5]. A 10% savings in operating costs has already been achieved in Beamish-Munro Hall, simply by changing the scheduling of air-handling fans based on building use patterns.

Special challenges: Planning the pedagogical use of the building HVAC systems required a core staff, including a consulting engineer assigned to developing the live building. This engineer held numerous meetings with the project's consulting engineers and hammered out the thousands of details that made up the system. This involved significant expansion of the number of air-flow, temperature, humidity, steam-flow, and other sensors over what would normally be present. Despite the large number of sensors, we soon found the need for additional data points, and a small sum was spent on subsequent expansion of the monitoring system.

Enthalpy wheel

One of the air handling units of the HVAC system does not feed air directly to any part of the building, and exists solely for the purpose of energy conservation. The enthalpy wheel conserves energy by exchanging both heat and moisture between the exhaust and fresh air streams. When there is sufficient temperature difference between inside and outside air, the wheel preconditions the air going to the other air handling units. Data available online show temperature, humidity, and airspeed from both sides of the wheel. This information is displayed in a real-time exhibit on the live building webpages.

The wheel was the first of its kind to be installed at Queen's University. It has been calculated that the wheel is saving the university $20 000 per year in energy costs. As a result of observing the performance of this unit, the University has installed two more wheels in new construction over the last three years.

Power monitoring

Electricity usage in Beamish-Munro Hall is measured by twenty-four meters throughout the building. These meters monitor the load on various distribution panels to illustrate the flow of power through an industrial system. There are also meters on the building's motion-controlled lights, standard hallway lights, HVAC fans, computer room, space heaters, and chiller. (See Fig. 2.) The live building database also gathers basic power-use data from most of the other buildings on campus, as well as data from the University's 14-megawatt cogeneration facility.

Special challenges: Power consumption varies greatly between buildings, and Beamish Munro Hall's particular mix of studio space, group rooms, construction bays and offices creates a unique power-usage profile that is difficult to compare with other buildings. Early decisions had to be made about what to measure and what type of metering to install in which locations, decisions that required educated guesses about the kind of information students would most benefit from receiving. During the planning process for this, as in other aspects of the live building, there tended to be mutual frustration between the consulting engineers who understood their specialty but perhaps not this unusual application, and the University's engineers and academics, who had a notion of what they would like to do but often little idea of what might constitute a cost-effective solution. The result was not always the best. Already, one multi-circuit meter has been moved, and others may follow as we learn more, and as new teaching opportunities present themselves.

The great complexity of the commissioning process resulted in mistakes being made, and several meters, even now, do not return proper values. Studies done at Texas A&M University suggest that 12% of energy meters are faulty or have been installed incorrectly [6]. Finding faults and determining solutions is a time-consuming process involving both the building operators and the University's maintenance engineers. Of course, even erroneous data have pedagogical utility; students learn to compare readings with other sources of data, with calculations and with 'common sense', perhaps developing more of the latter in the process.

Solar array

The live building incorporates data from a 20-kilowatt façade-mounted solar array, placed on

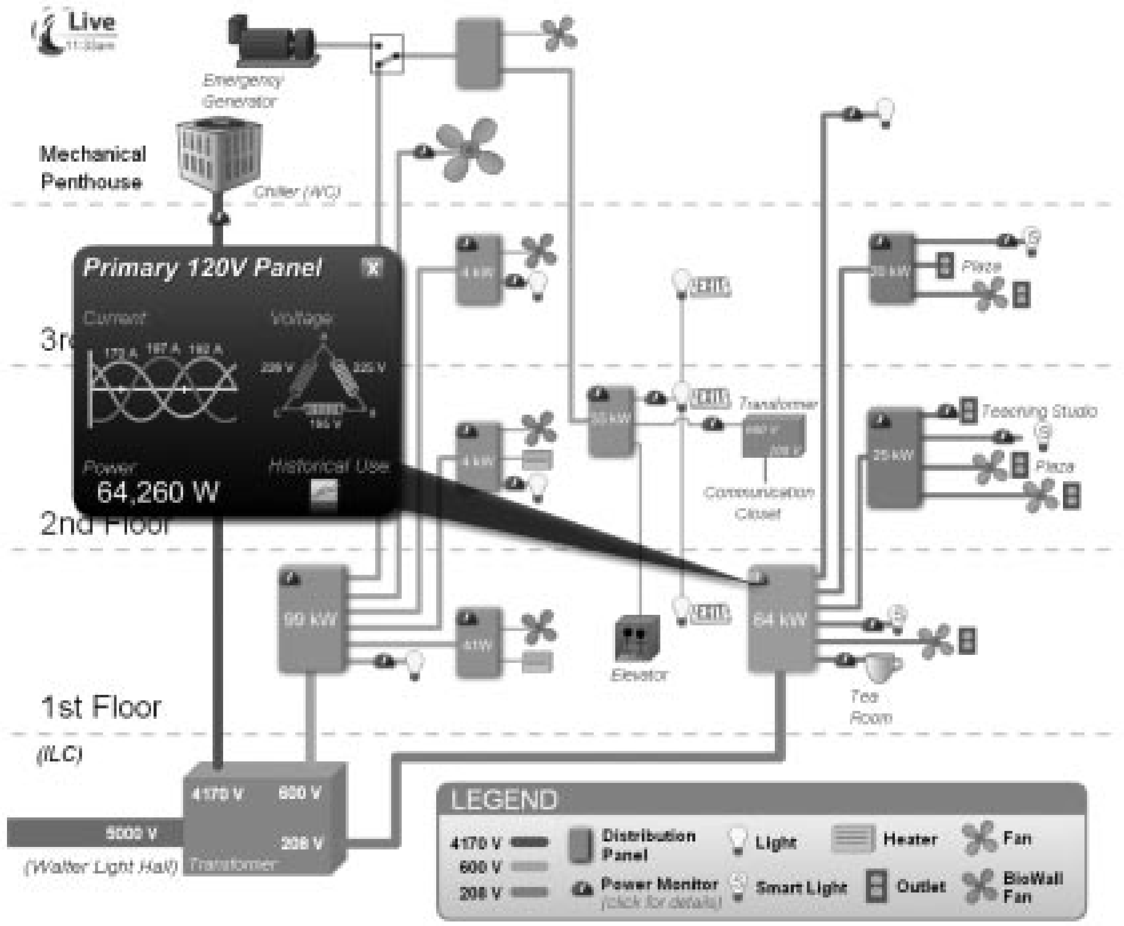

Fig. 2. Real-time flash display of the IL Center's electrical distribution system.

the top four floors of an adjacent seven-storey, south-facing building. The array was not formally part of the Integrated Learning initiative, having been put in to study the problems of large solar installations retro-fitted to older buildings in this part of Canada. However, it is connected to the live building system so that its performance—as an example of sustainable energy—can be monitored. The array produces an average of 20-megawatt-hours per year of electricity, serving approximately 10% of the electricity needs of the building on which it is mounted.

Biowall

The biowall improves air quality in the office wing of the building, provides an attractive aesthetic feature with great visual impact, and offers opportunities for study and experiment. It is the product of research performed at the University of Guelph into bioremediation of polluted air [7]. The wall, designed by Dr Alan Darlington and located immediately inside the main entrance, is three stories tall and is the first thing that students and visitors see when they enter Beamish-Munro Hall.

The roots of the plants on the wall are hosts to bacteria that digest volatile organic compounds (VOCs). The VOCs are typically given off by materials such as paint, carpeting and electronic devices. In sufficient concentrations, they can cause discomfort or even illness among the building's occupants. Air is drawn through the wall where it contacts the roots of the plants, and is circulated by fans to the office wing. In addition to removing VOCs, the plants reduce CO_2 levels.

One of the major issues in implementing the biowall was how to control it. For experimental purposes we wished to have the ability to control the air flow through the wall, by adjusting some combination of the three variable-speed fans. There also had to be mechanisms to control water flow and water salinity and to detect pump failures. A major question during the planning process was whether the biowall should have a separate monitoring system or have sensors that were an extension of the building automation system. In the end, only the water controls were kept separate, the rest of the system being integrated into the main HVAC control system.

Learning column

The learning column is a non-structural column below a structural beam. The column is located over a footing that is part of the building's foundation structure. A hydraulic jack located between this footing and the base of the column allows anyone to apply a load to the column and, through it, the beam. An array of strain gauges on the beam and column produce data that are displayed in real time, allowing the observer to see the deformation of the column and beam. The data are also recorded in the live building data base for later viewing and analysis.

Smart lights

Beamish-Munro Hall incorporates an energy-efficient lighting system, including the Agili-T system marketed in Canada by Canlyte. The choice of this system was controversial because the energy savings were not expected to repay the higher installation and maintenance costs. However, this was one of the times where the pedagogical value was felt to justify an otherwise questionable expense. Among many benefits of having this system, the motion-sensitive light data also provide a useful record of building utilization on a room-by-room basis.

The Agili-T system was expected to include a proportionality feature, in which just enough artificial light is produced to reach, in combination with available natural light, the target level for that location. However the manufacturer has not yet been able to provide this capability, an example of the sort of situation that can arise when one adopts new technologies

Exterior wall

During construction, thermistors were embedded at the interfaces between the various layers of the exterior wall on the west side of the building. A diagram of this is available on the live building website with real-time data on the temperature measurements, which can be compared with ambient conditions measured by a weather station located on the roof of an adjacent building.

Multiple glazing types

The glazing in the west wall of the building is of several different types, with solar heat gain coefficients ranging from 0.13 to 0.51. This is an example of having given up some energy efficiency for the sake of a learning opportunity. Sensors have been designed to measure the heat and light transfer of the windows; these are being manufactured at the time of this writing.

Weather

The facilities include a weather station mounted on the roof of Walter Light Hall, a seven-storey building adjacent to Beamish-Munro Hall. The weather station went online in early 2004 as part of the solar-array project, and included sensors for temperature, humidity, wind speed and direction, and solar radiation. The station was upgraded in 2005 to a Davis Vantage Pro2 wireless station that additionally provides a rain tip bucket, a pressure sensor, and a UV sensor. Weather data allow students to compare and correlate any of the building data with local climate conditions.

LIVE BUILDING DATABASE AND DATA ACCESS

There were two stages in the implementation of the live building system. The first was establishing the database, which unites all the data in a common format for ease of storage and provides a central point for student access. The second was connecting interfaces from commissioned building systems into the database.

Data from throughout the building are stored in an OSIsoft PI database. PI is an industrial real-time process-control system used commercially to track manufacturing processes. The software is capable of handling up to a maximum of thirty-two million data points at high polling and retrieval rates. The set-up and configuration of the data points from each building system was a non-trivial exercise. Each building management system uses a different software protocol; although OSIsoft provides over five hundred types of interface between PI and various automation and data acquisition systems, several custom solutions and some custom programming were still required. This process took place over many months, as the systems were commissioned and came online.

Live building showcase website

The website, located at www.livebuilding.ca , is the face of the live building system. Primarily designed to support undergraduate studies of the engineering elements, it also serves as an outreach tool for Applied Science, and as a public information source about buildings, sustainability, and education.

The site was created as more than just a data access point. It is intended to illustrate building technologies graphically, to answer common questions about the systems, and to demonstrate the functioning of various systems using interactive displays and real-time data. These displays include the air handling units in the building's mechanical penthouse (see Fig. 2), the learning column, the building envelope, the solar array, the biowall, and the multi-circuit power metering throughout the building and across campus.

The website follows the research-based United States Government usability guidelines [8]. Because of the high level of interconnection among the systems, the site was designed to use simultaneous navigation (as opposed to sequential navigation) in the form of drop-down menus. This allows users to explore topic areas easily and naturally. The pages were optimized for best display of graphical elements and 3D displays, to encourage a systems-level understanding of the information presented.

Website technical details

It is expected that engineering students will be the primary users of the webpages. These students have a higher than usual adoption rate for new technologies and software than the general public, so it was important that the site was not only usable in all web browsers, but that it used the most current web technologies to ensure that the site remains relevant in the face of future software upgrades. Hence the site is compatible with the World Wide Web Consortium (W3C) XHTML1.1 standards, the most current compliance rating.

The website makes use of one of the most popular Rich Internet Applications, Adobe Flash, to present real-time data in the interactive exhibits. The decision was made early on to use Flash over Java. Although Java is more powerful as a fully fledged programming environment, its power is more than is required for our data-retrieval requirements, and Java is less well suited than Flash to web graphics. Our emphasis was on creating displays that were attractive and that contain effects that make the engineering behind the systems easy to visualize. Flash is well suited to these objectives, and incorporates snap-in database and socket connectors that allow any heavy programming to be done on the server side. The Flash browser plug-in is free, and likely to be installed already on the computers of many students. The use of Flash technology for some of the interactive exhibits does cause some problems for screen-reading software, but alternative text is provided for these pages.

Also, a historical record of the raw building data is available via a simple text request form, so that it can be imported easily into Excel or MATLab. Alternatively, an application is available that connects directly to the PI database and streams data in real time to the client's computer. The application, developed at Queen's, takes input in user- and machine-readable extensible markup language (XML), allowing students to craft their own scripts to access building data, using any programming language. One interesting use has been in several art projects created by students, where the art would change as a result of data received in real-time from the live building database. In one piece, various colors of water would shoot out of a fountain in response to Beamish-Munro Hall's real-time power consumption, and in another piece a dynamically-generated graphic was generated through a data projector in response to wind speed.

TEACHING AND LEARNING

The usage of the live building as part of formal coursework is extensive, and is growing at a brisk pace.

The data from the HVAC system have been used for courses in process control, in building energy systems, and in design. A number of student projects have used HVAC historical data for modeling and for cost–benefit analyses. A mechanical engineering course in instrumentation incorporates a live HVAC component into each lab section, where students analyze data from temperatures and pressures in the building as a supplement to their labs on the same topics. Data from the enthalpy wheel on the transfers of energy and moisture between the two air flows are used in calculations of energy savings and hence of cost-effectiveness. Data are used in both courses and projects.

And simply as a vast deposit of meaningful data, HVAC data provide rich material for courses in statistical analysis.

Analysis of the electrical metering data has been used in both coursework and project work. Projects have shown that the fans for the air-handling units, along with the chiller in the summer, are by far the largest consumers of electricity, amounting to between a third and a half of the building's total power use. When students analyze the data online and do cost calculations, they obtain an understanding of the financial impact of industrial machinery. Graphs that can be generated on the website illustrate power-use trends over days, weeks, months and years, demonstrating the impact of building occupancy on power consumption. (See Fig. 3.)

Several student projects have compared the power-consumption patterns of Beamish Munro Hall with those of other buildings on campus. Some have designed an ideal 'green' alternative building or made recommendations on power-saving retrofits to existing buildings. Within Beamish-Munro Hall, data have been used by students to demonstrate the feasibility of producing power for certain loads by retrofitting with fuel cells, including projects that looked into the costs of using fuel cells to replace Beamish-Munro Hall's backup power generator and to power the building's sustainable café.

Upper-year student projects have studied the effectiveness of the lights' control system, determining that the lights are falsely triggered approximately 11% of the time. Another project installed light sensors in suitable locations and developed 'daylighting' control algorithms for these sensors, adjusting the lights in response to the amount of daylight coming through the windows. Similar projects have examined the cost-effectiveness of various aspects of the building, including the lights, and several fourth-year electrical engineering projects are based on creating an intelligent control system for the window blinds.

Some of the student groups in a first-year problem-based learning course have monitored the performance of the biowall and offered suggestions for design improvements. One discovery has been that VOC data are affected by the placement of the reference sensor. This is an example of students learning not only the specific technology (biowall) but also learning to be mindful of ensuring that their measurements are meaningful. Such multiple lessons are central to integrated learning. Continuing studies of the biowall, by biology students as well as engineering students, are expected to lead to future improvements in its operation.

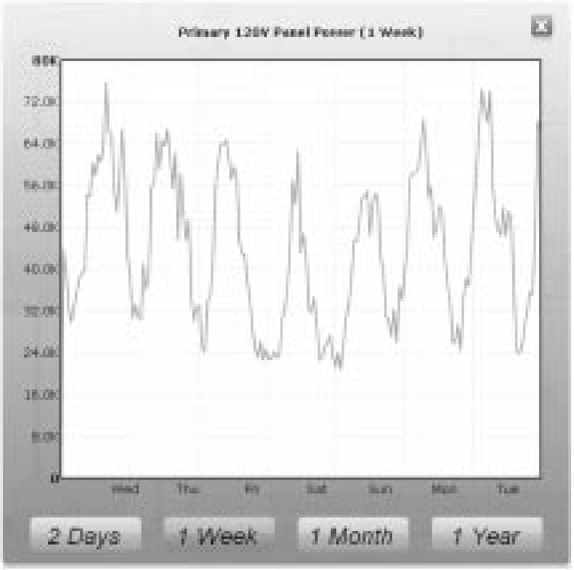

Fig. 3. A power-use graph generated on the fly demonstrating power trends a week prior to the request-date.

The learning column has been popular both in contributing to civil engineering courses in properties of materials and in structures and also as an item of general interest to passers-by. Students can immediately see data reflecting compression in the column and the stress applied to the I-beam. They can use this information to plot stress–strain relationships. The experiment is equipped with a touch-screen display, so that any student or visitor can spend a few minutes applying load and watching the strain change as they do so; thus anyone can gain some insight into the behavior of building components.

Courses in thermal transfer use the data for heat passage through the wall, and will soon be able to use data from the various window glazings. Students can quickly estimate the exterior wall's R-values from the real-time diagram on the website, or get more precise values by downloading archived data from the database and calculating the wall's efficiency in different seasonal conditions, when the building is either losing heat or gaining it.

The teaching and research value of the solar array was a major consideration in the decision to erect it, and since its installation it has served as a data source for a course on alternative energy sources, and as a basis for several undergraduate student projects on sustainable technologies and green energy. The array has also been featured in several research papers, and is currently being used in a doctoral research project.

While there are many examples of the use of live building within formal teaching in courses, where the student is directed and the outcome assessed, a major objective of Integrated Learning is improvement of the quality and quantity of learning. Teaching plays a role in this, of course, but a great deal of learning from the Live Building occurs without any teaching, and the extent and nature of such independent learning are difficult to measure. Without doubt, there are students whose curiosity is aroused about matters well outside their own curriculum, and who learn about something that they would otherwise not know at all. Only 30% of the people using the online live building data are engineering students in our own Faculty.

PROBLEMS AND OPPORTUNITIES IN CONSTRUCTION AND IMPLEMENTATION

Planning the live building was of course an integral part of the general planning of the building structure. The University's planning team had to follow the work of the consulting engineers closely, seeking the best ways to insert displays and sensors at the most useful locations. Significant effort went into finding departmental or faculty sponsors for live building ideas, so that we had some confidence that they would be used. In some cases there was clear support, as with the Learning Column, where members of the Civil Engineering department had definite ideas about how they would use this feature. In other cases, where the support was not so strong, we installed boxes and ran conduit so that sensors and data acquisition equipment could be added later if and when needed. Some ideas, like the multiple glazing types and the temperature sensors embedded in a wall, had no sponsors but seemed like useful ideas and had to be part of the original design since they could not economically be retrofitted.

It is said that 'the Devil is in the details', and this is certainly appropriate to the construction of a highly sophisticated building with many unique attributes. The usual complex interactions among the owner, architect, consulting engineers, prime contractor, and sub-contractors become even more tortuous when there are many novel elements with which no one has experience. The additional work involved in incorporating the live building components did not adversely affect the budget, but it did contribute to delays because of the increased coordination required among trades. Commissioning was a particular challenge because the large number of sensors resulted in a long list of deficiencies, and many disputes about responsibility for resolution. Some of these deficiencies remain unresolved. Implementation of the live building is a work in progress that will go on for many years.

Nevertheless, a large amount of data is available, both real-time and historical, and even the imperfections of some of the measurements have educational value. One of the constant challenges in engineering education is encouraging the students to think about the data. Does it make sense, or is it affected by an equipment fault or a measurement error? The building provides a working industrial system with thousands of opportunities for students to compare measurements with specifications and to form judgments about real-world engineering systems and processes.

CONCLUSION

Despite teething troubles, which were to be expected, the live building has been a success. For a modest increment in the capital cost of the building, and about 50% of a technologist's time for ongoing implementation, maintenance and student support, we have a novel tool to enhance the learning experience in Queen's University's engineering programs. The live building, especially its website component, also constitutes an excellent outreach and public relations vehicle, and the use of live data exposes students to real-world situations rather than to simulations. Since the fully-coordinated web pages came online in September of 2006, use of the live building in the formal teaching program has grown gradually, and the web site has seen steadily increasing usage. During that half-year period, there were 30,000 unique visitors, about a third of whom visited the site at least 9 times. The most popular portions of the web site are the weather station (10% of all visits), and the biowall (9%).

Coursework also utilizes the directly observed, non-website elements of live building, such as the exposed structural features, the learning column, the solar array, and the biowall. These also have a broader educational impact, outside of any coursework, for everyone who uses the building

There remains potential for much broader use of the HVAC data and the vast variety of power measurement data for courses and projects. Since the current website came online, interest in these applications, along with questions and e-mails from students and faculty about the building and what data are available, have increased markedly, and we fully expect this trend to continue into the future.

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James D. McCowan is Professor Emeritus in Chemistry and in Chemical Engineering, and is a former Associate Dean of the Faculty of Applied Science. Educated at the University of Toronto and the University of Cambridge. He spent five years with DuPont Canada before joining Queen's University. He chaired the committee that developed the Integrated Learning approach and also chaired the committee responsible for the design and construction of Beamish-Munro Hall.