Chapter 4

Case Study Approach to Green Chemistry Impacts on Science Facility Design and Operations: Regents Hall of Natural Sciences at St. Olaf College

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Regents Hall of Natural Sciences at St. Olaf College exemplifies the substantial impacts green chemistry exerts in the design and operation of STEM related learning spaces. The principles of green chemistry align well with the guiding principles for facility construction, and they offer users and design teams opportunities to redesign and rethink systems. This case study reveals qualitative and quantitative deliverables associated with an implemented green chemistry laboratory curriculum. Feedback between building vision, mission and green chemistry yielded substantial energy and cost savings, attention to safety, design simplicity, open sight lines, low ambient ventilation noise and an inviting feel in the built laboratory facility.

In 2009, Doxsee published a chapter in the *ACS Symposium Series* describing the potential of green chemistry to permit broad access to chemical experimentation in facility independent ways (*1*). Furthermore, he posited that institutions and learners experience broad benefits from a green curriculum, specifically calling attention to issues of safety and cost savings. This chapter is not meant to provide a comprehensive review of green chemistry. It explores the impacts of green chemistry on facility design using a case study approach coupled to the framework suggested by Doxsee. Regents Hall of Natural Sciences at St. Olaf College serves as the subject of the case. While the design of the Regents

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Hall chemistry laboratory spaces were informed by a department commitment to pilot and implement a green chemistry focused lab program, we explore the influence of green chemistry in the broader context of STEM education facilities and operations. We express, in qualitative and quantitative ways, the impacts of green chemistry on 1) chemical safety related to chemical procurement, storage and wastes; 2) engineering controls; 3) laboratory layout and design; and 4) costs, including energy and operations.

Regents Hall of Natural and Mathematical Sciences consists of a 195,000 square foot new natural science building and an 18,000 square foot renovated mathematical sciences building connected by an 8,000 square foot link. The natural sciences and link portions of Regents Hall, housing biology, chemistry, physics, and psychology, opened in Fall 2008; the renovated mathematical sciences building, including mathematics, statistics and computer science, opened in Fall 2009. Interdisciplinary programs in biomolecular science and neuroscience also call Regents Hall home. The facility contains seven multi-level classrooms, eleven flat-floored classrooms, eight seminar rooms, four computational rooms, 26 teaching labs, 13,000 square feet of student-faculty research space, and an 8,000 square foot science library with individual and group study spaces. Unlike many science facilities, Regents Hall is organized by common functions and shared resources (equipment, instruments, and infrastructure) rather than by department. Chemistry occupies spaces found on two floors and in two wings of the facility, with neighbors that bridge to areas of the biological sciences. A description of how other facility-related decisions were informed by a wide range of professionals, the development of a common mission and vision, experimenting with space in our old building and promoting cross-disciplinary approaches to enhance efficiencies can be found in this volume, Chapter X (*2*). Additional details on the building design can be accessed elsewhere (*3–6*).

Green Chemistry

Green chemistry represents a philosophical shift in the practice of chemical science to broader systems thinking. At its core, green chemistry is resource management and pollution prevention at the molecular level. Formally, green chemistry is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances (*7*). In practice, green chemistry encourages a critical focus on the hazard component of the risk equation.

Risk = the <u>probability</u> that <u>exposure</u> to a <u>hazard</u> leads to some undesired <u>outcome.</u>

In short, risk = *f* (exposure, hazard).

As such, green chemistry requires scientists and engineers to examine the life-cycle impacts of the chemicals and chemical processes used to study natural phenomena, manufacture new materials and create commercial goods. It calls practitioners to make strategic choices using this broad set of information. Reframing chemical questions into life-cycle-systems-thinking is similar to looking at the operation or design of a building as a complex system - a living organism that achieves multiple goals through optimization (*8*, *9*). Green chemistry taps scientific creativity, interdisciplinary approaches and innovation to pursue the design and discovery of the next generation of chemicals and materials so that they augment what we mean by performance and value to include multiple environment and human health outcomes.

In making a commitment to green chemistry, the St. Olaf College chemistry faculty recognized the need to develop this kind of mindset in its graduates and in its operations. The chemical literature is filled with calls for a shift in chemical thinking to address substantive challenges, such as, improvements to chemical water treatment (*10*), expansion of green polymers and packaging (*11*), and changes to analytical methodology (*12*, *13*). Shulte (*14*) argued that green chemistry bridges occupational safety and health to sustainability. Recently, Andraos and Dicks (*15*) conducted a comprehensive review of effective green chemistry practices in higher education. They note a series of green chemistry payoffs and identify areas for improvement in teaching and research that parallel experiences of the St. Olaf faculty and student learning mentioned by Doxsee (*1*).

Green Chemistry and Facility Planning

Visionary teams connect green chemistry to facility operation and the planning processes for new or renovated science facilities. The organizational construct of the Regents Hall design team and the development of the project principles are detailed in Chapter X (*2*). The return of a colleague from a National Science Foundation (NSF) green chemistry workshop at the University of Oregon initiated a major shift within the St. Olaf College chemistry department. Workshop participants performed sophisticated synthetic transformations without the need of resource-intensive fume hoods or other kinds of specialized ventilation. Immediately our colleague pitched the idea of moving to a green chemistry focus in our synthesis laboratory as a way to cope with aging and unreliable infrastructure. Others quickly recognized the potential of green chemistry in other parts of the curriculum, and an externally funded effort was soon underway to pilot green chemistry in the first three years of the laboratory curriculum.

Crossover participation between the green chemistry team and Regents Hall design team formed a critical bridge. The colleague involved with the green chemistry workshop was one of the former facility planning project Faculty Shepherds. A second member of the green chemistry team served on the facility design team as the chemistry department representative during the last four years of design and construction. Their presence and work allowed green chemistry ideas and pilot project results to move into facility planning deliberations, and the facility planning questions fed back into their green chemistry work. Connecting green chemistry outcomes to the mission and vision of the facility formed another key component in making the feedback system work effectively. The guiding principles for the Regents Hall complex were known as the *Seven I's*, and they are shown in Table 1. Whenever the Design Team generated new ideas, considered design elements or questioned a course of action, these principles were used as an internal check; to be adopted, options generally had to address at least three of the seven principles.

Table 1. Guiding Principles of the Seven I's

Interdisciplinary	How does the design preserve rigorous exploration of the current disciplines while enhancing interdisciplinary inquiry, teaching and learning?
Investigative	How does the design promote the expression of our investigative approaches to science and math?
Interactive	How does the design promote the interactive nature of modern science (student-student, student-faculty and faculty-faculty)?
Innovating	How does the design accommodate the technological and pedagogical innovations of modern science education and adapt to emerging educational strategies and technologies?
Interconnected	How does the design show the interconnections between the sciences and other distinctively St. Olaf strengths? How does the design reinforce awareness of the interconnectivity of physical space and linkages beyond the building envelope?
Inviting	How does the design invite students, faculty, staff and visitors to explore the space, encourage them to linger and inspire them to work and learn?
Integrity	How does the design model the integrity we seek, honor the environment in which it resides and reflect the college's continued commitment to environmental stewardship? It must also allow the faculty to fulfill the charge of the college mission statement to: 1) stimulate students' critical thinking and moral development; 2) encourage students to be seekers of truth, leading lives of unselfish service to others, and; 3) challenge students to be responsible and knowledgeable citizens of the world.

Green chemistry strongly coupled to a number of these guiding principles: interdisciplinary; investigative; innovating; and integrity. The ability to ascertain the hazard characteristics of a material relies on different sets of knowledge – physical, biological, and chemical - coming together in a way that moves beyond the disciplines. In order to infuse green chemistry into the laboratory, we investigated what others had previously contributed to green chemistry education. We mapped green chemistry principles onto the first three years of the chemistry laboratory program (Table 2). Then we undertook faculty-student collaborations to develop and pilot green chemistry learning experiences in our old facility; we call this innovation (*16–21*). Integrity is captured by the broad green chemistry vision at St. Olaf College: to prepare the next generation of chemical explorers to be sensitive to the impact the chemical profession has on the local and global environments; to apply creative problem solving skills to issues related to building a sustainable, just, global society; and to ask questions, seek answers, engage others and act responsibly. Overall, green chemistry provided the chemistry department and design team with opportunities to rethink and redesign. It helped the teams think broadly about systems, educational goals and what it means to do good chemistry.

Table 2. Distribution of Green Chemistry Principles across the Lab Curriculum[a]

Required Lab Courses **Green Chemistry Principles**	general chemistry	intro to physical chemistry	synthesis I	synthesis II	analytical	physical
Prevent waste	▨	▨	▨	▨	▨	▨
Maximize atom economy			▨	▨		
Design less hazardous chemical syntheses	▨	▨	▨	▨	▨	
Design safer chemicals						
Safer solvents and auxiliaries			▨	▨	▨	▨
Design for energy efficiency			▨	▨	▨	
Use renewable feedstocks	▨		▨	▨	▨	▨
Reduce or avoid chemical derivatives				▨	▨	
Catalysis			▨	▨		
Design for degradation			▨	▨		▨
Analyze in real time to prevent pollution						
Accident prevention	▨	▨	▨	▨	▨	▨
# of principles exemplified in curriculum	4	3	9	10	7	5

a. shading indicates principle is covered in this part of the lab curriculum

The teams discovered synergies between the green chemistry principles and the credits used in the Leadership for Energy and Environmental Design (LEED) program of the United States Green Building Council (USGBC). LEED is a third party analysis tool developed to address building lifecycle issues and to recognize best-in-class building strategies. To be certified in one of four levels, building projects must satisfy prerequisites and earn points (credits) based on design and construction decisions (*22*). Many of those design points dovetail with green chemistry concepts. For example, in the LEED Materials & Resources section, the use of locally sourced materials and high recycled content relates to waste prevention and the use of renewable feedstocks, green chemistry principles 1 and 7. Energy efficiency in chemical reactions (principle 6) connects to the LEED Energy and Atmosphere credits. LEED credits associated with indoor chemical/pollutant source control and low-emitting materials map onto the design of safer chemicals, solvents and auxillaries (principles 4 & 5). The effectiveness of these synergies was recognized when Regents Hall of Natural Science became the first academic wet lab facility to achieve a LEED Platinum rating (*23*, *24*).

Impacts: Chemical Procurement, Storage, and Wastes

Waste prevention undergirds many of the green chemistry principles. In the practice of chemical education, many people may be responsible for the cycle of chemical procurement, storage, waste accumulation and disposal. In order to enhance communication among those charged with executing a hazardous material information system, renovations or new construction creates an opportunity for synergistic arrangement of spaces and personnel. Figure 1 shows the case in Regents Hall; the biology and chemistry department stockroom managers play prominent roles in managing chemical materials and share an office immediately adjacent to the large service stockroom and chemical storeroom. The chemical hygiene officer occupies an office located across the hall from this stockroom; consequently, the three principal players involved in hazardous material management are in close proximity to one another. This small team collectively manages chemical storage and waste accumulation locations throughout the building. The primary chemical storage and waste accumulation area is located adjacent to the building's loading dock; this arrangement facilitates transfers into and out of the facility. Recessed floors in this area will contain chemical spills of a variety of magnitudes. Computer network access and power is located immediately outside the storage spaces so that databases related to inventory and waste management can be readily accessed, updated and shared.

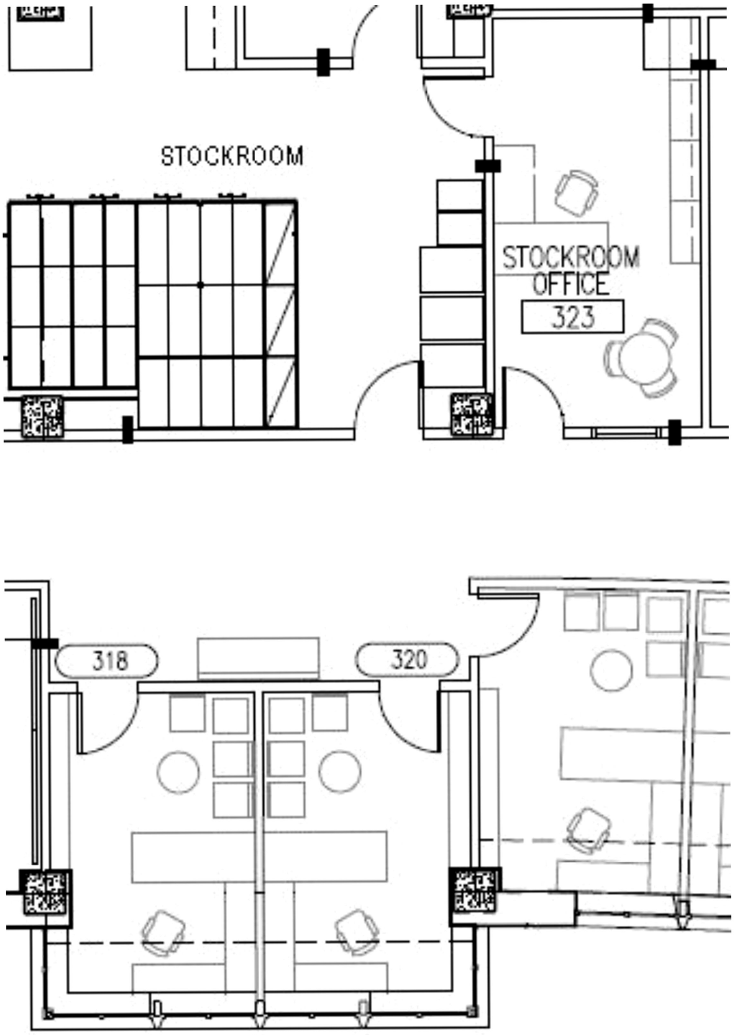

Figure 1. Proximity of personnel responsible for chemical procurement, storage and wastes. Biology and Chemistry stockroom managers share an office (323) located near the Chemical Hygiene Officer (318) and connect to the main service stockroom.

Beginning in 2004-05, St. Olaf College implemented a new waste management system, and the chemical synthesis faculty piloted green chemistry laboratory experiments. The total liquid hazardous waste generated by the synthesis laboratory course decreased by over 30 percent in the three year pilot (Table 3). The amount of hazardous waste generated depends on the characteristics of the chemical processes, the number of students enrolled and the proficiency under which those enrolled carry out their work. In an effort to minimize variation in hazardous waste generation from fluctuations in student numbers, waste outputs were normalized by the respective annual enrollments. The amount of hazardous waste generated per student decreased by more than 20 percent over the three year pilot period, highlighting the effectiveness of green chemistry in waste prevention.

Table 3. Hazardous Waste Generation in Synthesis Laboratory Green Chemistry Pilot

Academic Year	*Annual enrollment*	*Haz waste (L/yr)*	*Per capita waste (L/student yr)*
2004-2005	290	103	0.36
2005-2006	300	95	0.32
2006-2007	248	70	0.28

Impacts: Engineering Controls and Layouts

At the time of our initial facility design, the chemical profession emphasized engineering controls as a means to address the risk of chemical exposure, including development of ductless chemical fume hood systems (*25*) and alternative fume hood designs (*26*). The chemistry department initially supported this direction, planning to incorporate 2.5 feet of fume hood space per student in our teaching laboratories. Poor product yields and difficult physical manipulations associated with microscale synthesis and sporadic operation of aging constant volume chemical fume hood infrastructure fueled this vision. Concerns about the acquisition and installation costs of the alternative fume hood designs and the life cycle impacts of filters used in ductless hoods led the department to pursue more traditional fume hood designs. The chemical sciences and facilities managers would certainly benefit from additional life cycle analysis of newer ductless fume hoods and their filtration systems.

The success of collaborative undergraduate research in forwarding green chemistry development in the curriculum (*16–21*) led to a change in the way the design team looked at engineering controls for managing risk associated with chemical use. If we could effectively teach the practice of chemistry without large numbers of functional fume hoods in our old facility, why not examine how that would carry into a new facility? The design team proposed the removal of one-third to one-half of the originally planned fume hoods. The architects and users recognized this change would mean additional flexibility in the layout of the laboratories as the sizes of the air handling systems decreased. Facilities personnel and the project engineers identified initial cost savings and recurrent savings to operations. Users began to think of laboratory spaces as dual function learning environments, having the potential to serve as both classroom and laboratory. The impacts of green chemistry on learning space design mentioned by Doxsee - design simplicity, open sight lines, low ambient ventilation noise, an inviting feel, and a productive work environment - became manifest (*1*, *3*, *4*).

The removal of nearly forty percent of the chemical fume hoods yielded the benefits highlighted in Table 4 and in Figures 2-5. Most notable is the footprint formerly associated with a chemical fume hood, now available for reassignment. We calculated this footprint as the area of the fume hood plus an additional work zone extending out four feet from the fume hood. The work zone allows traffic to move safely past users at the fume hood. For standard 36 inch deep 4-ft, 6-ft, and 8-ft fume hoods, this yields 28, 42 and 56 ft^2 of assigned floor space, respectively. When summed together, the total space available for reassignment in Regents Hall was 1700 ft^2. When compared to our 315 ft^2 laboratory design module, this represented 5.4 laboratory design units – very substantial space! In addition to floor space, fume hoods occupy wall space. We calculated a 'wallprint' using the distance from the former hood work surface (34 inches) upward to a 7 ft reference line the architectural team set for wall installations. Approximately 1300 ft^2 of wall space became available for other uses.

Table 4. Floor and Wall Space Gained by Reduction in Fume Hood Numbers

Timepoint	*# hoods*	*% decrease*	*floor*[a]	*wall*[b]
Initial facility plan	88			
Constructed facility plan	53	39.8	1700	1300

[a] Floor space now available for other uses (ft^2).

[b] Wall space now available for other uses (ft^2).

The availability of 3,000 ft^2 of assignable wall and floor space leads to substantial design flexibility and an open character to the laboratories, as illustrated in the layouts and photographs exhibited in Figures 2-5. The introductory chemistry labs (Figures 2 and 3) demonstrate exceptional sight lines, and an entire wall of windows provides views to the outside. Movable lab tables with edge mounted electrical strips powered through floor boxes allow for different interior spatial arrangements and promote dual uses. The space may house an integrated class/lab experience for up to 32 students or host a class when laboratory activities are not underway. Water, both tap and deionized, as well as space for small, dedicated equipment is available around the periphery. Infrastructure for projection technologies is available above the ceiling tiles.

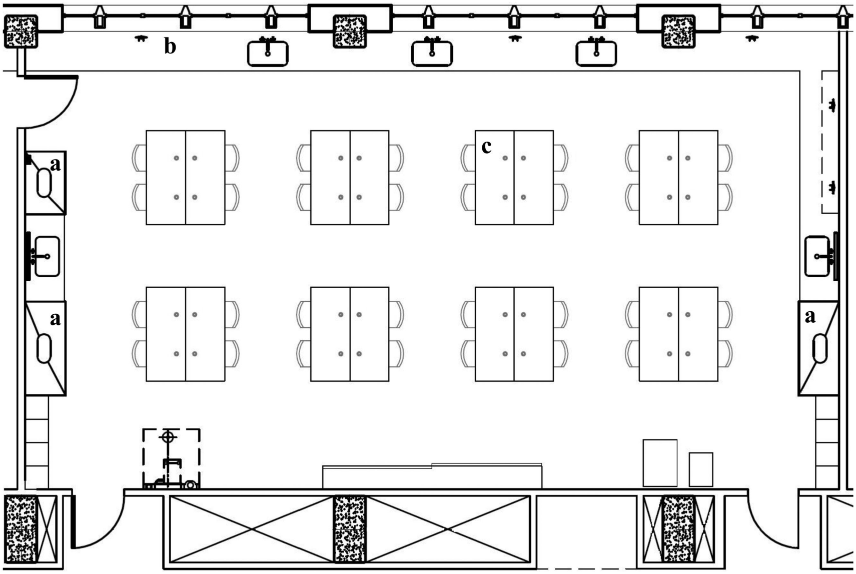

Figure 2. Laboratory layout for general chemistry. (a) Two six foot and one four foot hoods occupy interior walls, (b) exterior wall comprised of large windows and counter space for small equipment, and (c) moveable tables powered from floor boxes occupy the interior.

Figure 3. Introductory chemistry laboratory space that emphasizes green chemistry. Small equipment and sinks are located around the periphery while movable lab tables occupy the interior and allow for different configurations.

Sophomores typically explore organic and organometallic chemical synthesis in our curriculum. Figures 4 and 5 display the design of our synthesis teaching lab. Similar in many ways to the introductory lab in hood configuration and sight lines, this lab space uses fixed benches to allow additional storage of synthetic products and intermediates. Work with high hazard materials is moved out of the sophomore level synthesis labs and into advanced laboratories and collaborative spaces for undergraduate research and inquiry. *These latter space categories were designed with the 2.5 linear feet of hood access per user in mind and preserved the ability to employ chemical approaches where no substantive green chemistry alternative exists currently.*

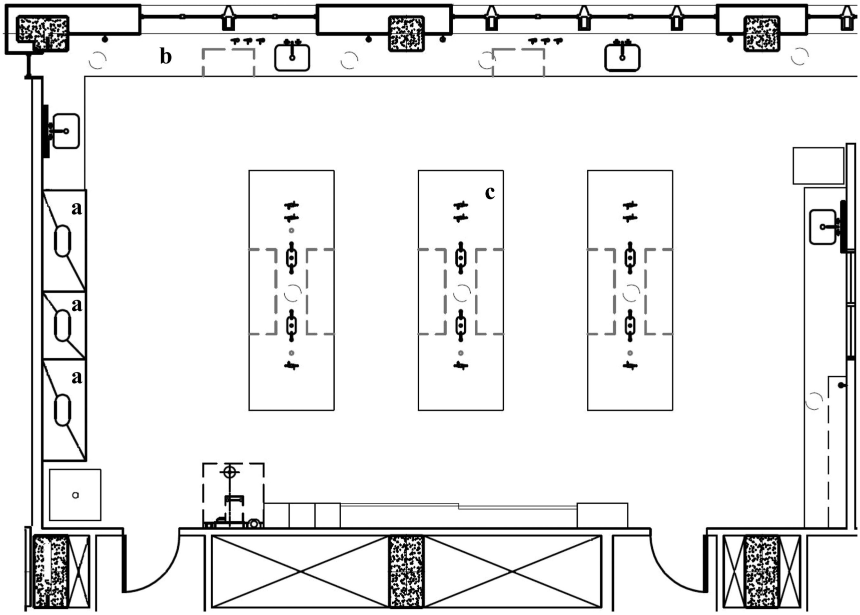

Figure 4. Laboratory layout for chemical synthesis. (a) Two six foot and one four foot hoods occupy one interior wall, (b) exterior wall comprised of large windows, and (c) fixed lab benches provide work surfaces and storage.

Fewer fume hoods allowed engineers to decrease the mechanical footprint required to condition and move air through the laboratories. Attention to chemical containment permitted the project to establish performance benchmarks for fume hoods at 50-60 ft/min linear velocities rather than at the much higher velocities used in our previous facility. The emphasis on hood performance (containment) and costs led the design team away from alternative hood designs. Considerations of the 24 hour, weekly, monthly and annual duty cycles of the lab spaces and fume hoods permitted us to create a user selectable standby status for hoods not in use. All of these factors further decreased the noise associated with laboratory air exchanges and assisted the project in meeting both the college's building requirements and LEED criteria. Most surprising was the discovery that the heating, ventilation, and air conditioning (HVAC) loads in our laboratories shifted from a fume hood dominated system to one determined by thermal energy released by people and the laboratory equipment. To some degree, the laboratory spaces in chemical sciences began to resemble laboratory spaces used in the biological sciences.

Figure 5. Students doing green chemistry in the sophomore level synthesis laboratory. Note the sight lines, fume hoods, windows, storage, and work areas present.

Impacts: First Costs and Operating Costs

Any time a large scale project has an infrastructure dependent system removed from the plans, substantial financial savings follow. Our construction manager calculated the average costs associated with each chemical fume hood at approximately $40,000, including the purchase of the hood, ductwork, controls, electrical, plumbing, etc. (*27*). Removal of the 35 hoods as a result of green chemistry commitments yielded a first cost savings of $1.4 million; this represents 2.2 percent of the total project costs. This money was leveraged and reinvested into the project to meet sustainability metrics.

Additional savings are realized from facility operations. It costs roughly $1000 to $1500 annually to operate each fume hood in the climate of Minnesota, and the reduction in the number of fume hoods translates into $35,000-50,000 saved in annual operations. Further energy savings result from a cascade air distribution system that employs glycol heat recovery loops and a low-flow variable air volume (VAV) laboratory exhaust system. Separate lab and public air supplies create the cascade air system in the facility. Outside air, conditioned using heat recovered from the glycol coils in the laboratory exhausts, is first passed through the classrooms, public and office spaces then returned and mixed with fresh air at the air handlers feeding the laboratory spaces. The mixing of returned air from the public side with fresh air preconditions the outside air to the 55 °F distribution temperature as it is sent to the laboratory spaces. If needed, a steam fed reheat coil supplements the VAV boxes to reheat the air when it reaches the desired space. Above an outdoor air temperature of -12 °C (10 °F), the effectiveness of this coupled heat recovery, air cascade system minimizes the steam heat supplied from the college's central plant.

Overall building performance, as measured by electrical energy use, has exceeded our expectations. The DOE-2 building energy models (*28*) suggested that if the facility was simply constructed to the Minnesota building code, annual energy use was estimated at 8.9 million kWh. Pursuit of design strategies incorporated into the facility predicted energy use at 4.9 million kWh. The first two years of operations posted energy use at 2.7 million kWh and 2.2 million kWh, respectively, as systems were optimized. This represents energy savings of 75 percent over the code requirements and almost 50 percent over the model with the design elements included. This highlights what integrated planning coupled to green chemistry can yield. According to St. Olaf College Assistant Vice President of Facilities, "We are operating at one-third the predicted costs." (*24*).

Impacts: Students and Staff Productivity and Perspectives

A nearly decades long planning process allowed the Design Team to strategically experiment with old spaces, frequently seek user perspectives, and assess laboratory spaces in a pre/post study. Results of that work (*3*, *4*) suggest a strong relationship between student perception, learning experiences, and the design of spaces in which the learning occurs. Increased student numbers in biology (10%), chemistry (45%) and physics (100%) suggest an inviting learning space and may reflect a broader appeal of the sciences. Since the 2008-09 opening of Regents Hall, the number ofsenior chemistry majors increased from an average of 42 to 61. Similarly, the physics department observed a substantial increase in majors from 12-15 per year into the upper 20s. These observed increases were explicitly excluded from facility planning due to budgetary and other institutional constraints. We are uncertain about the specific factors contributing to the student interest; however, our assessments reflect that the overall environment for student learning is enhanced in Regents Hall.

Conclusion

Our experience in the design, construction and operation of Regents Hall of Natural Sciences at St. Olaf College showed the substantial impacts green chemistry has on the design and operation of STEM related learning spaces. The principles of green chemistry aligned well with the guiding principles for facility construction, and they offered the users and design team opportunities to redesign and rethink systems. Energy and cost savings, attention to safety, design simplicity, open sight lines, low ambient ventilation noise and an inviting feel were delivered in this facility. As a result, we have a building that supports green chemistry, includes flexible learning spaces, exemplifies thoughtful stewardship of resources, and welcomes all to engage in STEM learning.

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