Brilliant Execution of Smart Labs: Employing Best Practices to Improve Safety and Reduce Energy for Sustainable Labs

Preprint

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National Renewable Energy Laboratory

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Brilliant Execution of Smart Labs: Employing Best Practices to Improve Safety and Reduce Energy for Sustainable Labs

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ABSTRACT

Laboratory buildings often dominate the energy use on research campuses, consuming three to four times the energy of a typical office building. In most cases, these facilities are defined as "mission critical," with excessive energy use that cannot be avoided without compromising safety. However, case studies indicate cost savings opportunities of up to 40% in laboratories (compared to standard practices) by employing energy efficient design strategies that also improve the safety of lab spaces (Better Buildings 2018).

To help stakeholders implement improvement measures, the Smart Labs Toolkit describes a proven approach to optimizing performance of laboratories and critical control environments in new or existing facilities. The Toolkit outlines distinct phases for building a successful Smart Labs program that include: Plan, Assess, Optimize, and Manage. Each phase has specific tasks, training videos, and resources to educate users, support the efforts of key stakeholders, and maximize benefits for the organization in implementing high-performance labs. The Toolkit also includes case studies from the 17 Better Buildings Smart Labs Accelerator partners, sharing lessons learned and supporting the Smart Labs approach to safe, efficient world class science.

This paper reviews the technology choices for implementing Smart Labs ventilation strategies, controls, and other efficiency measures. Better Building Smart Lab Accelerator partners provide case study examples of safety and energy-savings results of using Smart Labs approaches.

Introduction

Laboratory research is vital to the advancement of scientific discovery. This often makes cutting-edge science the sole driver for the reputation, growth, and profitability of research institutions across the globe. As a result, organizations spend tremendous capital building laboratories to attract skilled researchers with safe, high-performing workspaces that support leading scientific research, inspire innovation, and bolster success of the organization.

Researchers depend on proper design and operation of the building systems to provide safe, controlled lab spaces that support their scientific endeavors. The complex, challenging nature of laboratory facility operation often leads to disjunction between occupant safety, research needs, and building system capacities. Many laboratory buildings suffer significant, persistent operational issues that hinder success of lab activities, increase waste, and negatively impact the health of the organization (Smith 2004; Matthew et al. 2007; Kaplowitz et al. 2012). As a result, a typical laboratory is 3 to 4 times more energy intensive than a typical commercial office building (Better Buildings 2018). Based on the Labs21 database of 614 lab facilities, the average site energy use intensity for a single lab is 319 kBtu/ft^2-yr (Shehabi et al. 2017), 4 times greater than that of a typical office building, 78.7 kBtu/ft^2-yr (McDonald and Shankar 2016).

When left unresolved, excessive energy use causes undue financial burden on institutions, inhibiting the ability to fund research and improve facilities. Improper system design and operation can degrade facility performance, compromise integrity of research, deter top talent, and cause irrevocable harm to people, property, or the environment.

Despite the magnitude and widespread nature of poor system performance in laboratories, resources for resolving these performance and safety issues are difficult to come by. Furthermore, the complexity of research facility operation on an organizational level makes knowing where to begin improvements a daunting task for stakeholders.

This paper presents the approach of implementing a Smart Labs program that optimizes performance of laboratories and critical control environments in new or existing facilities through systems-based management coupled with advanced monitoring and control technologies. When implemented successfully, a Smart Labs program often achieve significant benefits, including:

- Safe, healthy workspaces that prioritize the safety of researchers and staff
- Reduced energy consumption and lower operating costs
- Reduced building systems degradation, deferred maintenance, and property loss
- Increased returns on investment with risk reduction for the organization
- Attraction and retention of top-talent researchers with high-performance lab spaces.

Specifically, this paper highlights Smart Labs best practices for optimization of airflow, implementation of dynamic building systems, and incorporation of additional efficiency in laboratories. These best practices are included in a public online platform called the Smart Labs Toolkit (I2SL 2020a), providing a cohesive collection of resources to guide laboratory stakeholders through the straightforward, holistic Smart Labs approach to achieving dynamic, high-performance laboratories.

Definition of Smart Labs

Smart Labs are defined as laboratories that enable safe and efficient world-class science to occur through high-performance methods. The Smart Labs program employs a combination of physical, administrative, and management techniques to assess, optimize, manage, and maintain high-performance laboratories. Highlighted best practices include:

- Minimizing risk by reducing the quantity of hazards and using less-hazardous substitutes
- Containing hazards primarily within exposure control devices, such as fume hoods
- Optimizing airflow patterns for high ventilation effectiveness
- Preventing hazard re-entrainment with model-informed exhaust and intake system design
- Implementing demand-based, dynamic building systems through precision controls, sensors, software, and ongoing commissioning
- Minimizing fan energy through low pressure drop design and fan optimization
- Using high-efficacy lighting systems and controls to achieve low lighting power density.

The History of Smart Labs

In the late 1990s, the Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE) established the Labs for the 21st Century initiative (Labs21) to improve the safety and performance of laboratory buildings. The program developed an early toolkit of resources containing best practices, education, and training to advocate a whole-building approach to enhancing energy efficiency and environmental performance in labs. Today, the program continues under the leadership of the International Institute for Sustainable Laboratories (I^{2}SL).

In 2008, University of California Irvine (UCI) engineers discovered their lab facilities accounted for 65% of total campus energy consumption, despite exceeding California energy code and composing only 20% of the campus building area (Van Geet et al. 2018). Building off the work of Labs21, UCI began the Smart Labs Initiative to question current best practices in laboratory design and reduce their energy use baseline for the campus. Through the Smart Labs Initiative, the UCI campus reduced energy use by an average of 60% in 10 lab buildings, with a payback period of 6–8 years (UCI 2018). With such tremendous success, UCI became the flagship for Smart Labs initiatives at other institutions.

In 2017, DOE created the Better Buildings Smart Labs Accelerator (BBSLA), a 3-year DOE-funded program that provided support to 17 partners committed to reducing energy use in labs by at least 20% over the next 10 years and implementing no- to low-cost measures for short-term energy savings of 5% by 2020. Over the period of BBSLA, partners achieved 103,000 MBtu in total energy savings, exceeding goals with an average 11% improvement across their building portfolios (Better Buildings 2020).

Smart Labs Best Practices

Minimize the Risk

The first step to achieving smart, safe, and efficient laboratories is to minimize risk in the lab space. Choosing less-hazardous chemical substitutes when possible reduces the opportunity for exposure, resulting in safer lab environments, reduced building system loads, and minimized environmental impact of research waste.

To effectively minimize risk, the Smart Labs approach includes educating research staff on alternative chemicals and procedures through training programs and publicly available resources. For example, the publicly available MilliporeSigma’s DOZN Tool (www.sigmaaldrich.com/chemistry/greener-alternatives/matrix-scoring.html) assists researchers in identifying the impact of certain chemicals based on the 12 Principles of Green Chemistry aimed at improving human health and the lab environment through the reduction of exposure to hazardous materials.

Contain the Hazard with Exposure Control Devices

In some cutting-edge research practices, the use of hazardous chemicals and procedures is unavoidable. To prioritize safety in Smart Labs, exposure control devices (ECD) should be correctly implemented to contain hazards at the source and prevent exposure to occupants present in the laboratory environment. The most common ECD is a fume hood, defined as “a safety device specifically designed to carry undesirable effluence away from laboratory personnel and out of the building, when connected to a properly designed laboratory system,” according to the Scientific Equipment and Furniture Association (ASHRAE 2015). Additional ECDs include snorkels, glove boxes, and chemical or biological safety cabinets.

Proper selection, sizing, and placement of ECDs are critical to ensuring the safety of the occupants and reducing energy use. Incorrect ECD installation can lead to inadequate face velocity, rendering the ECD ineffective in controlling occupant exposure to hazards. In this case, the ECD both fails in its primary function of protecting the immediate and long-term health of occupants and unnecessarily increases energy use through inefficient operation.

Selection of the appropriate ECD depends on the laboratory activities and chemicals involved. A thorough ventilation risk assessment and survey of activities and associated hazards, including method, rate, and quantity of generation, should be conducted in determining the proper ECD (I^2SL 2020h). For example, fume hoods contain general odorous, toxic, and otherwise harmful substances used in a wide range of laboratory procedures, whereas biological safety cabinets specifically prevent organisms and infectious agents from contaminating other projects, personnel, and the environment. Sizing and placement subsequently rely on the ventilation risk assessment and a survey of the existing ventilation system to ensure necessary ECDs with adequate face velocity for proper operation are provided for expected lab activities.

Operating specifications of ECDs must strike a delicate balance of effective operation and energy consumption that prioritizes safety of the users. To effectively reduce energy use without compromising safety, flow rate across the ECD face area can be optimized to the lowest level that provides adequate containment. In the case of fume hoods, installing a sash stop at a height of 15" limits the face area, allowing the hood to be balanced at ½ the flow rate required for the face area with fully open sash (typically 30"). Pairing with a variable air volume (VAV) exhaust system maximizes energy savings by further reducing the flow rate in times of disuse.

Automatic sash closing systems that use occupancy sensors can be installed; however, the best sash closing system is an educated, proactive user. The Colorado School of Mines, a BBSLA partner, achieved cost savings of approximately $12,000 through a “Shut the Sash” initiative in the largest lab building on campus, Coolbaugh Hall. The campus-wide program is projected to save up to $30,000 per year ($I^2$SL 2020b).

Optimize Airflow Patterns

Air is the primary carrier of contaminants, heat, and moisture in a laboratory building, making the laboratory ventilation system the first line of defense against occupant exposure to research-related airborne hazards. Vital to a safe research environment, laboratory HVAC systems are also often the most resource-intensive building systems in critical research facilities, typically accounting for between 30% and 50% of initial construction costs (ASHRAE 2015). Based on data from 760 U.S. laboratory buildings, ventilation is the largest consumer of energy, accounting for up to 47% of total energy use (I^2SL 2020g). Because of their complexity, laboratory HVAC systems require the greatest level of effort for operation and maintenance. In this regard, these systems often offer significant opportunities for reducing operational costs.

A key Smart Labs strategy for laboratory ventilation systems is optimizing the airflow patterns that determine the concentration of contaminants and indoor air quality in labs. These in turn lead to efficient, effective HVAC system operation, directly affecting the safety of occupants and cost savings.

In general, 100% outside supply air should sweep across the lab space and exit through exhaust grills or exposure control devices, effectively clearing contaminants from occupied workspaces without significant recirculation and stagnation, as illustrated in Figure 1.

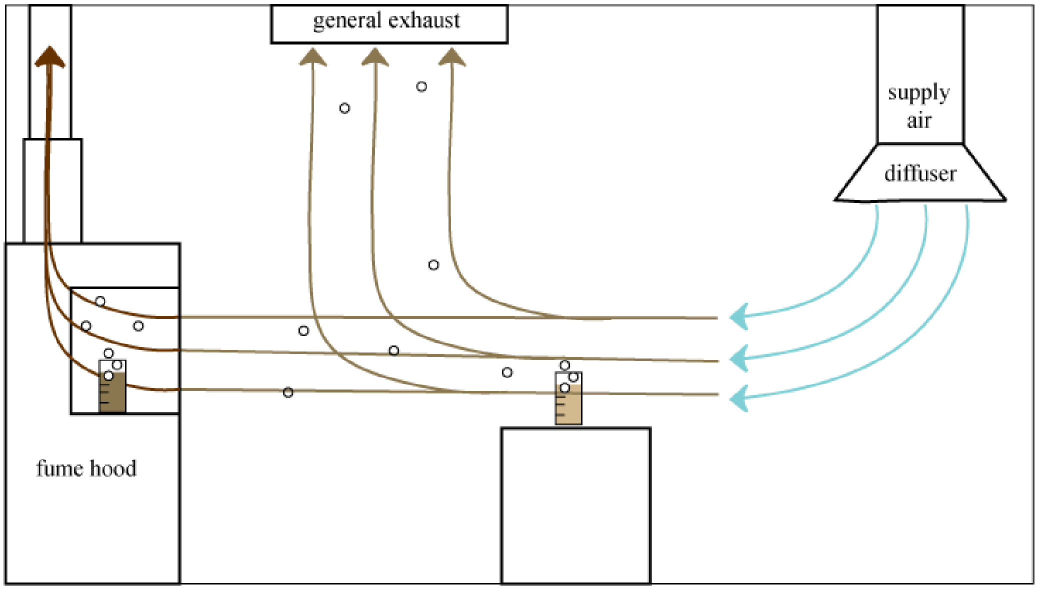


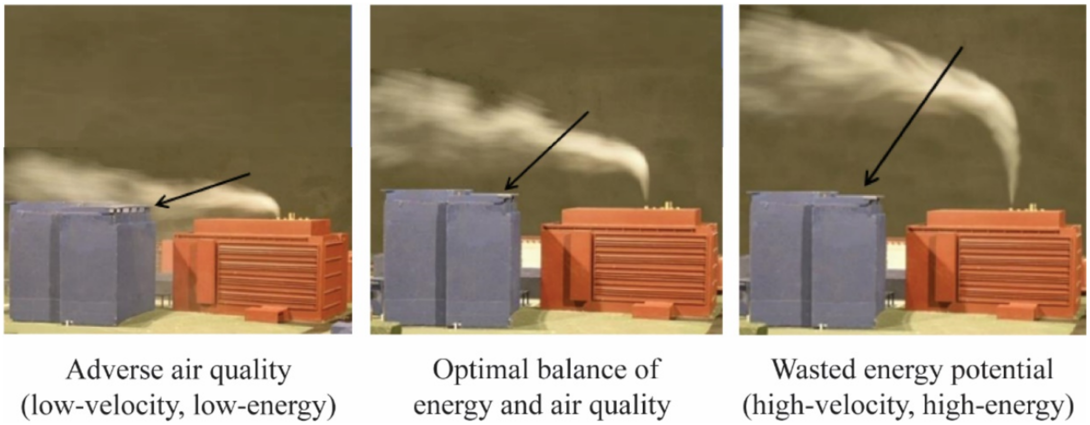
Fig. 1. Diagram of proper lab ventilation system. Clean supply air enters the lab via a diffuser at one side of the lab space, sweeping across the lab and capturing contaminants that are effectively removed through both general exhaust and exposure control devices, such as the fume hood displayed. *Source*: National Renewable Energy Laboratory (NREL) 2020.

Simple in theory, ventilation effectiveness depends on several interrelated factors that influence air velocities, temperature, and airflow patterns, including:

- Supply airflow rate or air changes per hour
- Location, type, and generation rate of contaminants
- Location, number, and type of air supply diffusers, exhaust grilles, and returns
- Location and strength of various heat sources in cooling-dominated labs
- Location and size of fume hoods in fume hood-dominated labs
- Arrangement of furniture and other airflow obstructions.

The complexity of lab ventilation makes it difficult to visualize the effects of different HVAC system components on airflow patterns. The interactive HVAC Resource Map for Laboratories (NREL 2020) describes best practices for supply-air, exposure control device, and exhaust-air design, including creating a three-dimensional model of airflow through a lab space using computational fluid dynamics to visualize specific impacts of different strategies. This allows Smart Labs program stakeholders to visualize how each strategy fits into the laboratory ventilation system and make informed decisions in implementing improvements.

Exhaust system design. Laboratory exhaust systems are responsible for effectively removing hazardous fumes from the interior lab environment, preventing re-entrainment of discharged exhaust in building supply air, and mitigating pollution of surrounding areas. Exhaust system standards often recommend higher discharge velocities than required to satisfy these responsibilities at the cost of high energy consumption. Through dynamic optimization of exhaust stack discharge, energy costs can be reduced while achieving effective contaminant discharge without re-entrainment or pollution of surroundings. Dispersion modeling using a wind tunnel or computational fluid dynamics is used to determine stack location, height, and discharge velocity to safely discharge fumes under different wind speeds and direction. As illustrated in Figure 2, wind-tunnel modeling allows laboratories to find the optimal balance between energy use in exhaust discharge and impact on surrounding air quality, especially when complex surroundings are present.



Adverse air quality (low-velocity, low-energy)

Optimal balance of energy and air quality

Wasted energy potential (high-velocity, high-energy)

Fig. 2. Images from wind-tunnel modeling of laboratory (red building) exhaust stack discharge. Arrows indicate the supply intake of an adjacent building to highlight the potential impact of laboratory exhaust. *Source*: CPP, Inc.

Recommended exhaust design employs either an active or passive VAV system, with exhaust flow matching supply flow at any given time. In passive VAV systems, exhaust flow is based on ventilation demand and the minimum air quality setpoint—the minimum flow/exit velocity/stack height needed to provide acceptable air quality at all locations as determined by the dispersion modeling assessment.

Active VAV exhaust system is a strategy that utilizes real-time monitoring of wind conditions with an anemometer to control stack discharge velocity, increasing or decreasing fan speed as needed to effectively disperse exhaust discharge contaminants. The results are then programed into exhaust system controls and used to inform fan speed adjustments based on the measured real-time wind conditions.

Incorporating energy recovery to use exhaust streams to preheat or precool incoming supply air is another best practice in reducing HVAC system energy costs. Laboratories require 100% outside air for ventilation with no recirculation to keep air quality at safe, acceptable levels and reduce potential for re-entrainment of hazardous airborne contaminants. While necessary, this requirement makes conditioning lab supply air energy intensive, especially in hot and cold climates. While multiple strategies exist, additional fan energy to overcome pressure drops through the energy recovery devices must be balanced with energy savings in all cases.

Dynamic Building Systems

Smart Labs are dynamic spaces that require dynamic building systems. Especially important in ventilation systems, catering directly to the needs of the occupants at all times and adjusting system operation as needed both enhances the quality and safety of the lab environment and results in cost savings.

One example is the use of occupancy sensors to adjust airflow based on occupancy. Airflow rate can usually be safely reduced during unoccupied times.

Another example is demand-controlled ventilation (DCV) using pollutant sensors to provide real-time VAV control. Ventilation air is provided at a minimum level according to ASHRAE Standard 62.1. Upon detection of a pollutant, such as carbon dioxide, carbon monoxide, or total volatile organic compounds, the ventilation rate is increased until pollutant concentration is reduced below a defined level.

While DCV requires ongoing coordination with site operations staff, the benefits of DCV extend beyond enhancing safety. DCV reduces ventilation rates to the minimum setpoint when designated pollutants are below the defined threshold. In labs in which ventilation rates cannot be reduced due to fume hood airflow needs, DCV can be implemented for pollutant detection and alarms. DCV systems also provide air quality and energy use reports, which can be used to report savings and identify malfunctioning equipment or poor lab practices that could otherwise go undetected.

Data analytics. Data analytics allow for continuous optimization of system operation to maximize return on investment of improvement measures. Detailed analytics ensure building systems are operating as designed, meeting new setpoints, air change rates, lighting levels, and occupied modes. Furthermore, managers can analyze long-term trends in building operation to identify further areas of improvement.

Analytics also provide a basis for verifying expected energy savings and justifying future improvement measures. NREL's Intelligent Campus platform exemplifies the integration of energy informatics into a facility's infrastructure, including the following use cases (I^2SL 2020d):

- Utility dashboard for energy management
- Energy reporting tools and facility dashboards
- Building operations and control
- Building systems fault detection & diagnosis
- Central plant operations
- Electrical distribution system operations
- Net zero energy measurement and verification
- Accurate tenant billing.

Ongoing commissioning. As system improvements are implemented, utilizing analytics and the facility's information layer for ongoing commissioning (OCx) has been identified as a Smart Labs best practice to maintain dynamic controls for high-performance labs, maximize savings and return on investment, and enable further Smart Lab optimization. The OCx approach involves using building analytics software to collect, store, and analyze data for energy and water consumption in laboratories. In a case study by BBSLA partner Lawrence Berkeley National Laboratory (LBNL), the team employed the OCx approach using SkySpark software that led to $410,000-plus in annual utility cost savings, with 5.7 million kWh of energy reduction and 18.9 million gallons of water reduction annually (I^2SL 2020c). Additionally, LBNL uses the DOE ISO 50001 Ready program to support their OCx process by ensuring that energy management activities are strategic, effective, and result in continual energy and water savings across LBNL's campus.

Additional benefits of ongoing commissioning include providing tools for continuous monitoring of the lab environment and equipment that support active management of fume hoods, workspace supply and exhaust systems, and entire-building ventilation systems. For example, involving the commissioning team in new construction allows for smooth transitions to effective operations.

Additional Efficiency in Laboratories

High-efficacy lighting. LED lighting is becoming the standard in most modern buildings, and LED lighting retrofits often result in better-quality lighting and lower energy use. The Smart Labs approach to lighting optimization goes beyond LED retrofits and occupancy controls to incorporate LED lighting in research-specific applications, including microscopy.

Plug loads. Plug loads are another energy-intensive area in laboratories targeted by approaches proposed in the Smart Labs Toolkit. Some lab equipment, such as autoclaves and ultra-low temperature freezers, run continuously in resource-intensive modes, even when not in use. In one case study, BBSLA partner U.S. Department of Health and Human Services Centers for Disease Control and Prevention (CDC) achieved 367,400 kWh/yr of combined savings during an Ultra-Low Temperature Freezer Initiative in 2017 (I^2SL 2020e). To achieve this amount of savings, the CDC's six labs consolidated resources by removing 8,798 samples from cold storage units, enabling them to retire 21 unnecessary ultra-low temperature freezers (I^2SL). Retiring those freezers resulted in an annual replacement cost avoidance of $31,500 per year ($I^2$SL). Combining the annual energy, maintenance, and replacement cost savings equal a total of $67,457 per year ($I^2$SL).

Equipment sharing. Equipment sharing platforms provide additional opportunities for enhancing sustainability efforts through the Smart Labs Program. In a recent case study on the BioCore Equipment Sharing program at the University of Colorado Boulder, the BioCore program saved over 2,000 square feet of lab space by removing underutilized instruments and furniture. Furthermore, the program resulted in significant financial savings by facilitating coordination between research groups, saving an estimated $856,000 in equipment costs and $39,000 in researcher hours paid (I^2SL 2020f). All reported savings were achieved within the first 18 months of program implementation as a result of internal support and buy-in by researcher staff.

Smart Labs Toolkit

Compiling best practices learned through the BBSLA, Labs21 efforts, laboratory hygiene professionals, and industry partners, the Smart Labs Toolkit (smartlabs.i2sl.org) guides institutions in developing a Smart Labs program to implement the dynamic, ongoing, four-phased Smart Labs process: Plan, Assess, Optimize, and Manage. The Smart Labs Toolkit is not a step-by-step recipe book for institutions to achieve facility optimization; rather, it creates a framework for a process with which a research institution can organize efforts to effectively continue optimizing laboratory facilities, as illustrated in Figure 3. Resources in each phase of the Toolkit include videos, worksheets, templates, and case studies from BBSLA partners on best practices learned in the successful development of a Smart Labs program.

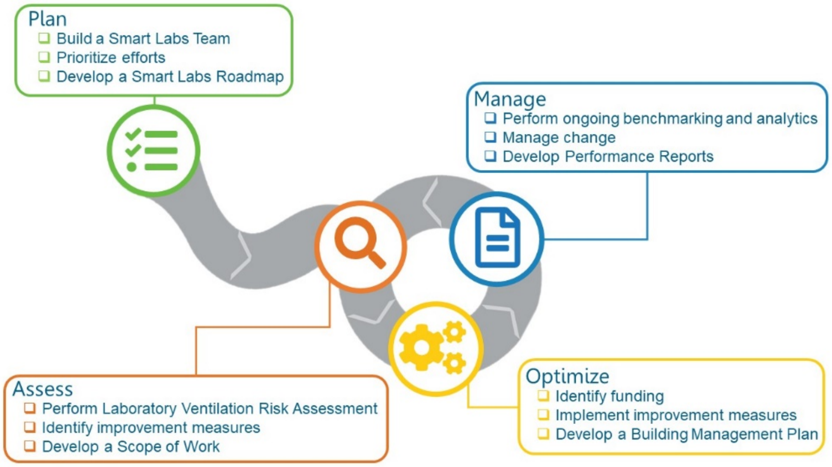


Fig. 3. A summary of the Smart Labs approach with a description of tasks accomplished in each phase. *Source*: NREL 2020.

Plan

Creating a Smart Labs program takes coordination, innovation, and a strong team effort, making planning essential to success. This section provides resources for how to start planning your Smart Labs program. Once a Smart Labs program is established, continue to revisit these planning resources as the program grows and matures and begin to expand efforts to the entire campus. In the Plan phase, organizations:

- Build a Smart Labs team of important lab stakeholders, including a Smart Labs coordinator, site operations personnel, and Environmental Health and Safety staff
- Prioritize laboratories based on benchmarking metrics
- Develop a Smart Labs Roadmap that outlines a plan of program actions and goals for prioritized laboratories.

Assess

Once the team has direction for the Smart Labs program, the next step is to thoroughly assess one building. Comparing these baseline performance metrics to design specifications and safety requirements informs the Smart Labs team of appropriate measures and opportunities to optimize laboratory system performance. The goal of the Assess phase is to identify areas in which the lab facility can be improved. The general steps in assessing all laboratory building systems include:

- Gathering available data, including floor plans, system schematics, and equipment inventory
- Performing system audits and surveys to establish operation baselines
- Identifying and developing a scope of work for improvement measures.

While the Toolkit presents methods for assessing all building systems, the focus of the Assess phase is the Laboratory Ventilation Risk Assessment™, a comprehensive process involving in-depth surveys of hazards and ventilation equipment to determine associated risk levels in each lab space. These risk levels, known as risk control bands, directly inform the air change rates necessary to maintain safe conditions.

Optimize

The Optimize phase involves appropriating funds and executing the scope of work proposed in the Assess phase. Laboratory buildings vary in age, size, function, and type of systems. Depending on the state of the systems, safety objectives, energy goals, and available funds, optimization projects can range from implementation of simple, low-cost measures to full-scale renovation of buildings involving highly complex and costly measures. This part of the toolkit includes guidance on:

- Identifying sources for project funding
- Implementing improvement measures, from system renovations to simple upgrades
- Developing a building management plan.

Manage

High-performance buildings are challenging to maintain, especially in laboratories, where changes in leadership, research staff, or best practices for safety and research procedures are frequent. The Smart Labs Toolkit includes advice on managing dynamic operation of laboratory facilities, a key principle of Smart Labs. Dynamic laboratory management includes:

- Ongoing benchmarking and analytics
- Establishing a system for effectively managing change
- Conducting lab safety surveys and staff training on a regular basis
- Developing a Smart Labs management plan with a campus-wide ventilation plan and specific building management plans for each building.

Working with Scientists

In addition to the four phases, the Toolkit includes best practices for communicating with researchers within an institution to encourage successful adoption of Smart Lab practices. In implementing a Smart Labs program, a vital step towards success is knowing the occupants and the research performed in lab spaces. Furthermore, safety is of the researchers' utmost priority in any Smart Labs program. Best practices for ensuring safety include engaging all personnel in the organization and educating researchers on alternative chemicals or procedures that both enhance safety protocols and minimize resource consumption.

Conclusion

The Smart Labs Toolkit provides a framework for research institutions to build successful Smart Labs Programs with dynamic, ongoing optimization of laboratory facilities. It outlines best practices that include minimizing the risk in labs, containing the existing hazards, optimizing the airflow patterns, implementing dynamic building systems, and more. It includes the lessons learned by BBSLA partners. These strategies provide a starting point for research institutions to question, improve, and "buck the status quo" of existing industry standards and achieve safe, dynamic, high-performance Smart Labs that provide optimal grounds for cutting-edge scientific discovery—without the environmental impact.

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