World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(Review Article)

Check for updates

Integration of Safety- first Design with Process Optimization in Engineering Technology Labs

Gbenga Rasheed Ajenifuja *

School of Engineering and Technology, Western Illinois University, Macomb, IL.

World Journal of Advanced Engineering Technology and Sciences, 2024, 13(02), 998-1006

Publication history: Received on 29 October 2023; revised on 27 January 2024; accepted on 27 February 2024

Article DOI: https://doi.org/10.30574/wjaets.2024.13.2.0610

Abstract

Engineering technology laboratories are dynamic environments that support practical innovation and process development. As demand grows for faster, more efficient operations, there is a pressing need to integrate safety-first design into process optimization. Traditionally, optimization efforts in laboratories have focused narrowly on performance, cost-efficiency, and throughput, often relegating safety considerations to post-design compliance measures. This fragmented approach has led to increased risks and missed opportunities for resilient system design.

This narrative review explores the integration of safety-first principles with process optimization frameworks in engineering laboratories. It examines established methodologies such as Lean, Six Sigma, and simulation modeling, while highlighting the importance of proactive hazard identification tools like HAZOP and FMEA. The review also discusses the emerging role of inherently safer design and multi-objective optimization models in bridging safety and performance goals.

Through a critical analysis of educational gaps, laboratory incidents, and evolving best practices, this study emphasizes the need for a cultural and institutional shift toward treating safety as a co-equal design parameter. It proposes practical strategies for embedding safety within engineering curricula and lab protocols, supported by case studies and policy recommendations.

Ultimately, the work advocates for a unified framework that ensures laboratories are not only efficient but also safe, sustainable, and aligned with real-world engineering expectations.

Keywords: Safety-First Design; Process Optimization; Engineering Technology Laboratories; Hazard Analysis Tools and Integrated Design Frameworks

1. Introduction

Engineering technology laboratories play a vital role in advancing practical innovation, hands-on education, and process development. As these environments grow more complex, there is increasing pressure to achieve optimal performance, speed, and resource efficiency. However, this drive for optimization must not overshadow the fundamental responsibility to ensure safety [1]. This disconnects between safety planning and process development increases the risk of accidents, equipment failure, and exposure to hazardous conditions for both students and staff.

Although the importance of safety is widely acknowledged, many labs still operate without a clear structure that incorporates safety considerations into the early stages of process design. Most optimization strategies tend to focus

* Corresponding author: Gbenga Rasheed Ajenifuja

narrowly on performance, cost, and operational efficiency, while safety is left to compliance checks or last-minute adjustments. As a result, potential hazards may go unnoticed until they lead to incidents [1,2].

This problem is further compounded by gaps in engineering education, where students often graduate without a strong foundation in how to design systems that are both safe and efficient. In real-world industrial settings, where safety and performance are inseparable, this lack of preparedness can have serious consequences. Ignoring safety during the design stage not only undermines the reliability of the system but can also compromise ethical and legal responsibilities [3,4,5].

There is a clear need for an integrated approach that brings safety to the forefront of process design and optimization. Such a framework should help engineers and researchers make informed decisions that balance risk, performance, and sustainability. By combining tools like hazard identification, inherent safety design, and multi-objective decision-making, laboratories can evolve into safer and more effective environments for learning and innovation [6,7].

This study seeks to address this gap by exploring how safety as a first principles can be seamlessly combined with process optimization in engineering technology labs. The goal is to establish a framework that enhances safety without compromising efficiency, ultimately promoting more responsible and future ready engineering practices. This work will examine current practices, highlight limitations in traditional approaches, and present examples of frameworks and tools that support safer and more effective process design.

The literature reviewed in this work draws from a diverse range of sources, including peer-reviewed journal articles, academic policy documents, incident case reports, and established best practices from recognized engineering safety organizations. Rather than following a rigid systematic protocol, this narrative review adopts a flexible, qualitative approach that allows for a broader and more exploratory understanding of the topic. This method is particularly well-suited to capturing the interdisciplinary and evolving nature of safety integration within process optimization frameworks.

The central purpose of this review is to encourage a cultural shift in the way engineering technology laboratories are designed and operated. It challenges the notion that safety must compete with efficiency or innovation, and instead argues that safety should be viewed as a foundational element of all process development. By emphasizing integration rather than separation, this review advocates for safer, more resilient, and ethically sound engineering practices that align with the realities of both educational and industrial settings.

2. Overview of Key Concepts: Safety and Optimization in Engineering Labs

To effectively explore the integration of safety-first design with process optimization in engineering technology laboratories, it is important to first understand the meaning and significance of both concepts. This section offers an overview of their core principles and examines how the connection between safety and efficiency has developed over time. By tracing this evolution, we gain insight into why these two areas once seen as separate are now being combined to create more resilient, efficient, and responsible engineering practices.

2.1. Process Optimization

Process optimization involves the systematic improvement of engineering processes to achieve more desirable outcomes such as higher efficiency, reduced waste, lower operational costs, enhanced product quality, and shorter turnaround times. In the context of engineering technology laboratories, optimization typically focuses on adjusting input variables, identifying ideal operating conditions, and employing computational simulations to enhance process performance while conserving resources [7].

Common tools used for optimization in laboratory and industrial settings include Lean principles, Six Sigma methodologies, response surface methodology (RSM), and process modeling software. These techniques are designed to streamline workflows, eliminate inefficiencies, and maximize value.

However, traditional approaches to optimization have often focused narrowly on productivity and cost-effectiveness, without fully accounting for potential safety implications. In some cases, this has led to process improvements that inadvertently increase risk or overlook critical hazards. As a result, there is a growing recognition of the need to integrate safety considerations directly into optimization efforts. Recent work in this area suggests that safety should be treated as a key performance metric evaluated alongside speed, cost, and quality to ensure that optimized systems are not only efficient but also resilient and safe for users [7,1].

2.2. Safety-First Design

The concept of safety-first design is grounded in the principle that potential hazards should be anticipated and addressed from the very beginning of the engineering design process. Rather than depending solely on protective barriers or emergency systems added later, this approach emphasizes building safety into the process itself. This may involve selecting safer materials, simplifying procedures, minimizing high-risk operations, or incorporating design features that reduce the chance of human error [1].

In engineering technology laboratories environments where students and researchers routinely interact with sophisticated equipment and potentially hazardous materials a safety-first mindset is paramount. Safety should not be perceived as a secondary concern or a regulatory obligation, but rather as a fundamental design objective, equally important as performance, efficiency, and functionality. By prioritizing safety from the outset of system design, laboratories can achieve greater resilience, reduce the likelihood of accidents, and enhance overall usability (1,5]. Embedding safety into the early stages of laboratory design ensures a proactive rather than reactive approach to risk mitigation [8].

Several structured methods support the application of safety-first design. Among the most commonly used are the Hazard and Operability Study (HAZOP), which systematically identifies deviations from normal operations; Failure Mode and Effects Analysis (FMEA), which anticipates how components might fail and what the consequences would be; and Layers of Protection Analysis (LOPA), which evaluates the adequacy of existing safety systems and the need for additional controls. These techniques, when applied early in the design phase, help engineers address risks before they escalate leading to safer, more reliable systems overall [1,4].

2.3. The Link Between Safety and Optimization

Safety and process optimization have often been viewed as separate, sometimes conflicting objectives. However, modern engineering practice increasingly acknowledges that the two are deeply interconnected. An optimized process that lacks adequate safety measures may operate efficiently under normal conditions but can become unreliable, costly to maintain, or hazardous in the face of disruptions. Similarly, excessive emphasis on safety if not balanced with efficiency can lead to overly conservative designs, reduced flexibility, and resource inefficiencies [9].

In reality, safety and efficiency often reinforce each other. For instance, simplification of procedures and the elimination of hazardous steps not only reduce risk but also streamline workflows and lower maintenance costs. Effective optimization strategies that consider safety from the outset can lead to systems that are more robust, sustainable, and easier to manage. It was argued that incorporating safety into multi-objective optimization frameworks enables engineers to make more informed decisions, achieving a balance between performance and protection. This integrated approach allows safety to become a driver of innovation, not a barrier [10].

2.4. Evolution of Safety Integration in Engineering Systems

The role of safety in engineering design has evolved significantly over recent decades. In earlier stages, safety was treated as a reactive measure typically addressed only after incidents had occurred or in response to external regulations. Design processes were primarily focused on functionality, speed, and cost, with safety introduced later through alarms, protective systems, or operating procedures. While these additions offered some risk reduction, they often failed to address the root causes of failure and tended to be costly when added post-design [11, 12].

A shift toward proactive safety integration emerged in the wake of major industrial disasters. Notable among these were the 1984 Bhopal gas tragedy, the 2005 Texas City refinery explosion, and the 1988 Piper Alpha oil platform disaster. These catastrophic events exposed the limitations of reactive safety models and catalyzed a broader move toward embedding risk management and prevention strategies into the early stages of engineering design [13,14].

This transformation led to the development of process safety engineering as a dedicated discipline. Techniques such as Hazard and Operability Studies (HAZOP), Failure Mode and Effects Analysis (FMEA), Layers of Protection Analysis (LOPA), and Inherently Safer Design (ISD) became standard tools in design practices [15]. These approaches enable engineers to anticipate and eliminate potential hazards before a system is built, rather than relying on barriers and redundancies after the fact [1].

The integration of safety into engineering curricula has also gained momentum. Increasingly, students are being trained to consider safety as an essential element of system design, not a regulatory afterthought. However, it has been highlighted that academic environments especially laboratory settings have yet to fully realize this integration. Many still operate within a framework where safety is managed administratively rather than embedded in process design [16].

Promoting a design culture that values safety as much as performance fosters accountability, sustainability, and long-term system resilience. It aligns educational practice with industrial expectations, better preparing students for the complexities of modern engineering systems [11].

3. The Current State of Process Optimization in Labs

Engineering labs increasingly adopt industrial optimization techniques to improve efficiency, accuracy, and resource use. Tools like Lean, Six Sigma, and statistical modeling help streamline lab operations and enhance performance. However, these methods often prioritize output over safety. This section explores current optimization practices in labs and highlights the need to better integrate safety into these processes.

3.1. Common Optimization Tools and Methodologies in Engineering Labs

Engineering laboratories today have adopted a range of optimization techniques originally developed for industrial applications. Among the most widely used are Lean manufacturing, Six Sigma, and Design of Experiments (DoE). Lean focuses on streamlining workflows by removing unnecessary steps, thereby enhancing efficiency and reducing waste. Six Sigma, on the other hand, employs statistical tools to minimize variation and improve overall process quality [17,18].

In addition to these, Response Surface Methodology (RSM) and the Taguchi method are commonly used in laboratory settings particularly in disciplines like chemical and mechanical engineering to fine-tune experimental conditions. These methods enable researchers to explore the effects of multiple input variables efficiently, helping them identify the most favorable combinations with minimal experimentation [19,20]. While RSM is based on statistical modeling and regression analysis to capture interactions between variables, the Taguchi approach emphasizes robustness by designing experiments that are less affected by external disturbances.

Modern software tools such as Minitab, Design-Expert, and JMP further support these methods by providing advanced data visualization, statistical analysis, and process optimization capabilities. With these tools, laboratories can enhance experimental accuracy, improve repeatability, and simulate real-world production conditions ultimately preparing students and researchers for industry-level problem-solving.

Despite their effectiveness in improving performance and efficiency, these optimization techniques rarely incorporate safety considerations directly into their frameworks. Their focus tends to remain on output metrics like yield, cost, and time, often overlooking critical safety dimensions. This limitation underscores the need for more integrated approaches that can evaluate both performance and risk within the same optimization process [21].

3.2. Simulation and Computational Modeling in Laboratory Optimization

Computational modeling and simulation have become vital tools in optimizing laboratory processes. Software platforms such as MATLAB, Aspen Plus, ANSYS, and COMSOL enable virtual experimentation, allowing researchers to test variables, predict outcomes, and improve system designs before any physical implementation. This approach significantly reduces time, cost, and operational risks [21].

Through features like sensitivity analysis, predictive modeling, and scenario testing, simulations support more informed decision-making during lab-scale process development. However, many simulation efforts remain performance-focused, with safety-related parameters either simplified or excluded entirely. This gap limits their ability to capture real-world hazards and system vulnerabilities during optimization. The failure to integrate safety into simulation models may result in optimized processes that perform well under controlled conditions but lack resilience in abnormal or high-risk scenarios [21].

3.3. Performance-Focused Objectives in Laboratory Optimization

Laboratory optimization efforts are often driven by performance goals such as increased throughput, improved resource utilization, reduced processing time, lower operational costs, and enhanced reproducibility. These objectives reflect industry standards and are intended to make academic labs function more like real-world engineering environments [19].

However, this strong focus on efficiency can sometimes overshadow safety. When risk assessments are not integrated into optimization strategies, potential hazards may go unaddressed. Treating safety and performance as separate considerations can weaken system robustness and expose users to unintended risks. Bridging this gap requires a shift toward integrated models that evaluate both safety and efficiency as co-dependent outcomes [1].

3.4. Academic Gaps and Educational Limitations

A significant barrier to integrating safety into laboratory optimization stems from how engineering education is structured. While most undergraduate and graduate programs offer thorough instruction in technical optimization methods, they often neglect to pair these skills with formal training in risk assessment and safety analysis [1,3].

As a result, students frequently approach process design with a focus on efficiency alone, lacking the systems-level thinking needed to recognize and mitigate potential hazards. This disconnect leaves them underprepared for professional environments where safety and performance are inseparable. To close this gap, educators and researchers increasingly advocate for the integration of safety tools such as Hazard and Operability Studies (HAZOP), Failure Mode and Effects Analysis (FMEA), and Layers of Protection Analysis (LOPA) into design courses and project-based learning. Embedding these tools within the curriculum would foster a more holistic understanding of process development and better align academic training with real-world engineering demands [4.5].

3.5. Emerging Multi-Objective Optimization Approaches

In response to the limitations of traditional performance-driven models, researchers have begun developing multi-objective optimization (MOO) frameworks that evaluate safety, efficiency, and cost as equally important factors in the design process. These advanced approaches utilize methods such as fuzzy logic, Bayesian networks, and genetic algorithms to incorporate both quantitative metrics and qualitative safety assessments into optimization models [22,23].

Unlike conventional optimization tools that prioritize measurable outputs alone, MOO models enable the inclusion of uncertain, probabilistic, and risk-related variables. This makes them especially valuable in laboratory environments where hazardous materials, complex systems, or human factors introduce variability and potential failure modes. By balancing competing objectives such as minimizing cost while maximizing safety these frameworks offer a more robust basis for decision-making.

Although these models are still emerging and not yet widely implemented in academic labs, their potential is increasingly recognized. They demonstrate that safety need not be sacrificed for efficiency, and that integrated solutions can enhance both resilience and performance in laboratory operations.

4. Safety Practices in Engineering Labs

Safety is a critical component of engineering laboratory operations, especially in environments where hazardous materials, high-voltage equipment, thermal processes, or pressurized systems are involved. While most academic institutions have established safety protocols, the effectiveness of these practices often depends on how early and thoroughly they are integrated into experimental design and workflow.

4.1. Overview of Standard Safety Protocols and Practices

Engineering laboratories, particularly those used for teaching and experimental research, are governed by established safety protocols aimed at minimizing risks to students, staff, and the environment. These protocols form the backbone of laboratory safety and are grounded in internationally recognized standards and guidelines.

Fundamental safety measures include the mandatory use of personal protective equipment (PPE) such as lab coats, gloves, goggles, and face shields. Proper labeling and storage of chemicals, including adherence to compatibility charts and segregation of hazardous materials, is essential to prevent unintended reactions and exposures. Well-designed ventilation systems, such as fume hoods and local exhausts, help contain volatile emissions and protect users from inhalation hazards [24]

Regular equipment inspection and maintenance schedules ensure that devices like autoclaves, ovens, compressors, and electrical instruments remain in safe working condition. Emergency preparedness protocols including spill control procedures, eye-wash and safety showers, fire extinguishers, and evacuation drills are implemented to manage accidents swiftly and reduce their impact. In most institutions, these measures are reinforced by mandatory safety training, orientation programs, and annual refresher courses for all lab users. [8,24]

Additional administrative controls include the use of risk assessment templates, standard operating procedures (SOPs), and laboratory safety audits, which provide systematic evaluations of lab practices and infrastructure. Key documentation like Safety Data Sheets (SDS) is expected to be readily accessible, either physically or digitally, to inform users about chemical properties, handling instructions, and emergency responses [24].

In well-managed labs, these safety elements are clearly organized and consistently enforced. Responsibilities are often delegated through designated lab safety officers, and visual aids such as hazard pictograms, signage, and color-coded markings enhance hazard awareness. However, research has shown that having safety protocols on paper does not always translate into real-world risk control. If safety measures are not fully integrated into the planning, design, and execution of laboratory activities, they may be underutilized or circumvented, particularly in high-pressure or unsupervised scenarios [8,11].

Thus, effective laboratory safety requires a culture of proactive engagement, where safety is not merely a compliance requirement but a shared value that shapes daily decision-making and design logic.

4.2. Common Hazards in Engineering Technology Labs

Engineering technology laboratories are inherently complex environments that involve various experimental setups, high-energy systems, and hazardous materials. This complexity gives rise to a wide array of potential hazards that, if not properly managed, can compromise both safety and productivity.

Chemical hazards are among the most frequent in engineering labs, especially in fields such as chemical and materials engineering. Users are often exposed to corrosive acids, flammable solvents, oxidizers, and toxic reagents. Accidental spills, incompatible storage, or inadequate ventilation can lead to chemical burns, respiratory distress, or even fire and explosions [24].

Electrical hazards also pose significant risks, particularly in labs focused on circuit design, control systems, or robotics. Exposure to live electrical components, poor insulation, and improper grounding can result in electric shocks, arc flashes, or electrical fires. These hazards are particularly dangerous when users lack formal training or operate equipment in wet or cluttered conditions [8].

Thermal hazards arise from the use of hot surfaces, steam systems, and cryogenic substances. Improper handling of furnaces, autoclaves, or liquid nitrogen can result in severe burns, frostbite, or pressure-related injuries. Often, these risks are exacerbated by inadequate thermal insulation, lack of PPE, or haste in experimental procedures.

Mechanical hazards are prevalent wherever rotating machinery, pressurized vessels, or cutting tools are involved. Loose clothing or jewelry can be caught in moving parts, while improper use of presses or grinders can lead to crushing, lacerations, or eye injuries. Inadequate guarding or bypassed interlocks significantly increase these dangers.[5]

In addition, ergonomic and physical hazards such as poorly designed work spaces, repetitive tasks, heavy lifting, or improper posture can lead to long-term musculoskeletal issues. Slips, trips, and falls, while often considered minor, remain a leading cause of laboratory injuries and are frequently linked to poor housekeeping or wet floors [11].

In more advanced or specialized labs, biological hazards (from handling microorganisms or cell cultures) and radiological hazards (involving X-rays or radioactive isotopes) may also be present. These require additional containment, specialized training, and ongoing monitoring to mitigate long-term exposure risks [24].

Because of the wide spectrum of hazards, engineering labs require not just adherence to protocols but an active commitment to identifying and mitigating risks as an integral part of the research and design process. When safety becomes embedded in everyday practice rather than treated as a checklist item labs become safer, more efficient, and better aligned with real-world engineering standards.

4.3. Limitations of Post-Design Safety Implementation

A major limitation in many academic labs is the reliance on post-design safety controls, where risk is addressed only after the process has been developed. This reactive approach typically involves adding protective gear, warning signs, or procedures once a process is operational. While such measures are helpful, they may not eliminate the root cause of hazards and can result in overcomplicated safety protocols that burden users without resolving underlying risks [11].

Moreover, post-design interventions often lead to fragmented safety management, where compliance becomes the goal rather than genuine hazard prevention. In contrast, integrating safety during the design phase through inherently safer design, risk-based layout planning, and simulation is more effective and sustainable [1].

4.4. Case Examples of Lab Incidents Due to Poor Safety Planning

Numerous incidents in academic settings underscore the consequences of inadequate safety integration. One widely cited example is the 2008 laboratory fire at the University of California, Los Angeles (UCLA), where a research assistant died due to improper handling of pyrophoric chemicals without proper PPE or supervision. The tragedy led to widespread reform in lab safety culture across U.S. universities [25].

In another case, at Texas Tech University in 2010, a graduate student was severely injured in a chemical explosion due to insufficient hazard analysis and pressure testing prior to experimentation [24]. Investigations revealed that safety protocols existed but were not effectively enforced or embedded in research planning.

These incidents highlight the urgent need for proactive, design-based safety strategies in engineering labs, where potential risks are evaluated and addressed during the planning phase, not just after processes are in place.

5. Bridging the Gap: Integration Models and Strategies

In engineering technology laboratories, there is a growing effort to bring together safety and process optimization through unified design strategies. Traditionally, these two goals were treated separately optimization focused on speed and efficiency, while safety was often addressed as a compliance step. Today, integrated frameworks are emerging that aim to close this gap. These approaches are designed not just to enhance performance, but also to embed risk management into every stage of the design process creating lab systems that are not only efficient but also safe, adaptable, and sustainable.

5.1. Integrated Safety and Optimization Frameworks

Modern frameworks increasingly promote concurrent design approaches, where safety and optimization are treated as co-equal objectives from the outset. Rather than optimizing first and retrofitting safety later, these models embed risk assessment tools into the optimization workflow. For instance, frameworks like Risk-Based Process Design (RBPD) and Safety Integrated Process Design (SIPD) incorporate both performance metrics and hazard mitigation criteria into early decision-making stages [1,10].

5.2. Role of Hazard Analysis Tools

Hazard analysis tools play a central role in integrating safety into engineering process optimization. Two widely adopted techniques Hazard and Operability Studies (HAZOP) and Failure Mode and Effects Analysis (FMEA) provide structured methods to identify and evaluate risks before they become critical issues. HAZOP helps uncover deviations from intended operations by systematically analyzing process parameters and their potential impacts, while FMEA prioritizes possible failure points based on their severity, occurrence, and detectability [24]. When incorporated during the early design or optimization phases rather than after implementation, these tools support proactive risk management and contribute to safer, more robust lab systems without diminishing process efficiency [11].

5.3. Inherent Safety Design

Inherent safety design is a preventative strategy aimed at reducing or eliminating hazards directly at the source, rather than relying solely on additional safeguards or procedures. This approach involves design choices such as selecting non-toxic or less reactive chemicals, simplifying process steps, reducing inventories of hazardous materials, and ensuring systems default to a safe state during failure [26]. Because these safety measures are built into the process itself, they align well with optimization efforts supporting goals like operational simplicity, cost reduction, and system resilience. Unlike reactive controls, inherent safety improves long-term sustainability and reduces dependency on human intervention.

6. Future Directions and Recommendations

As engineering laboratories evolve to accommodate more advanced processes and interdisciplinary learning, the need to integrate safety-first design with process optimization becomes increasingly critical. Moving forward, several key areas warrant attention to strengthen this integration in both educational and industrial contexts.

6.1. Embedding Safety into Design Curricula

One of the most pressing needs is the formal integration of safety analysis and risk-based thinking into engineering education. While optimization methods like Lean and Six Sigma are commonly taught, safety tools such as HAZOP, FMEA, and Layers of Protection Analysis (LOPA) often remain peripheral or elective. Embedding these tools into project-based learning, simulation exercises, and capstone designs can cultivate a mindset where students treat safety as a design parameter, not a constraint [1,8].

6.2. Advancing Digital and Simulation Tools

As computational modeling becomes more widespread, there is a need to develop simulation tools that incorporate safety metrics alongside technical ones. Most current platforms (e.g., MATLAB, COMSOL, Aspen Plus) are optimized for performance evaluation, with limited provisions for real-time risk assessment. Enhancing these tools with built-in safety models or integrating them with risk analysis software would allow users to visualize safety-performance trade-offs during the design phase [10].

6.3. Policy and Institutional Support

To promote lasting integration of safety and process optimization in engineering labs, institutional and regulatory bodies must play a more proactive role. Accreditation standards and educational policies should require clear evidence that safety practices such as HAZOP and FMEA are embedded in lab design and operations [24]. Providing funding, training, and recognition for safety-integrated programs can accelerate adoption. Collaboration with industry and safety organizations ensures alignment with real-world expectations [1]. Treating safety as a measurable performance metric, rather than an afterthought, will help institutionalize it alongside efficiency and innovation.

7. Conclusion

Engineering technology laboratories are essential environments for innovation, experimentation, and practical learning. However, the long-standing divide between process optimization and safety planning has left many laboratories vulnerable to preventable risks. This review has shown that while optimization techniques such as Lean, Six Sigma, and simulation modeling have improved efficiency and performance, they often fall short in proactively addressing safety.

By contrast, safety-first design prioritizes hazard elimination at the source and emphasizes risk management throughout the system life cycle. Tools like HAZOP, FMEA, and inherently safer design principles offer structured means to anticipate and mitigate risks. When these tools are integrated into optimization workflows from the outset, rather than appended as afterthoughts, laboratories can become both safer and more efficient.

The path forward lies in adopting integrated design frameworks that treat safety and optimization as complementary rather than competing objectives. This includes advancing multi-objective optimization models, embedding safety into engineering curricula, upgrading simulation platforms to include safety parameters, and enforcing institutional policies that mandate safety-performance integration.

Ultimately, fostering a culture where safety is viewed not as a barrier but as a driver of sustainable innovation is critical. Through this integrated mindset, engineering laboratories can better align with industrial expectations, enhance educational outcomes, and build resilient systems prepared for future challenges.

References

[1] Li, J., Goerlandt, F., Reniers, G., and Zhang, B. (2020). Sam Mannan and his scientific publications: a life in process safety research. Journal of Loss Prevention in the Process Industries, 66, 104140.

[2] .Kumar, A., Saw, R. K., and Mandal, A. (2019). RSM optimization of oil-in-water microemulsion stabilized by synthesized zwitterionic surfactant and its properties evaluation for application in enhanced oil recovery. Chemical Engineering Research and Design, 147, 399-411.

[3] Dhillon, B. S. (2017). Engineering systems reliability, safety, and maintenance: An integrated approach. CRC Press.

[4] Sträter, O. (2016). Cognition and safety: an integrated approach to systems design and assessment. Routledge.

[5] Leveson, N. G. (2016). Engineering a safer world: Systems thinking applied to safety (p. 560). The MIT Press.

[6] Thomas, R. S., Cheung, R., Westphal, M., Krewski, D., and Andersen, M. E. (2017). Risk science in the 21st century: a data-driven framework for incorporating new technologies into chemical safety assessment. International Journal of Risk Assessment and Management, 20(1-3), 88-108.

[7] Verma, S., Pant, M., and Snasel, V. (2021). A comprehensive review on NSGA-II for multi-objective combinatorial optimization problems. IEEE access, 9, 57757-57791.

[8] Hill Jr, R. H., and Finster, D. C. (2016). Laboratory safety for chemistry students. John Wiley and Sons..

[9] Yazdi, M., and Zarei, E. (2018). Uncertainty handling in the safety risk analysis: an integrated approach based on fuzzy fault tree analysis. Journal of failure analysis and prevention, 18(2), 392-404.

[10] Ghasemi, F., Ghasemi, A., and Kalatpour, O. (2022). Prediction of human error probability during the hydrocarbon road tanker loading operation using a hybrid technique of fuzzy sets, Bayesian network and CREAM. International Journal of Occupational Safety and Ergonomics, 28(3), 1342-1352.

[11] Leveson, N. G. (2011). Applying systems thinking to analyze and learn from events. Safety science, 49(1), 55-64.

[12] Kong, C. I., Welfare, J. G., Shenouda, H., Sanchez-Felix, O. R., Floyd Jr, J. B., Hubal, R. C., ... and Lawrence, D. S. (2022). Virtually bridging the safety gap between the lecture hall and the research laboratory. Journal of Chemical Education, 99(5), 1982-1989.

[13] Hopkins, A. (2008). Failure to learn: The BP Texas City refinery disaster. CCH Australia Ltd.

[14] Kletz, T., and Amyotte, P. (2019). What went wrong?: case histories of process plant disasters and how they could have been avoided. Butterworth-Heinemann.

[15] Medina-Herrera, N., Jiménez-Gutiérrez, A., and Mannan, M. S. (2014). Development of inherently safer distillation systems. Journal of Loss Prevention in the Process Industries, 29, 225-239.

[16] Soltanzadeh, A., Mahdinia, M., Omidi Oskouei, A., Jafarinia, E., Zarei, E., and Sadeghi-Yarandi, M. (2022). Analyzing health, safety, and environmental risks of construction projects using the fuzzy analytic hierarchy process: A field study based on a project management body of knowledge. Sustainability, 14(24), 16555.

[17] Baker, B. (2003). Lean Six Sigma: Combining Six Sigma Quality With Lean Speed. Quality Progress, 36(10), 96.

[18] Antony, J. (2006). Six sigma for service processes. Business process management journal, 12(2), 234-248.

[19] Montgomery, D. C. (2017). Design and analysis of experiments. John wiley and sons.

[20] Roy, R. K. (2010). A primer on the Taguchi method. Society of manufacturing engineers.

[21] Malakooti, B. (2014). Operations and production systems with multiple objectives. John Wiley and Sons.

[22] Khakzad, N., Khan, F., and Amyotte, P. (2013). Quantitative risk analysis of offshore drilling operations: A Bayesian approach. Safety science, 57, 108-117.

[23] Marhavilas, P. K., Koulouriotis, D., and Gemeni, V. (2011). Risk analysis and assessment methodologies in the work sites: On a review, classification and comparative study of the scientific literature of the period 2000–2009. Journal of Loss Prevention in the Process Industries, 24(5), 477-523.

[24] National Research Council, Division on Earth, Life Studies, Board on Chemical Sciences, Committee on Prudent Practices in the Laboratory, and An Update. (2011). Prudent practices in the laboratory: handling and management of chemical hazards, updated version.

[25] Shariff, A. M., and Norazahar, N. (2012). At-risk behaviour analysis and improvement study in an academic laboratory. Safety science, 50(1), 29-38.

[26] Abedsoltan, H., Abedsoltan, A., and Zoghi, Z. (2024). RETRACTED: Future of process safety: Insights, approaches, and potential developments.