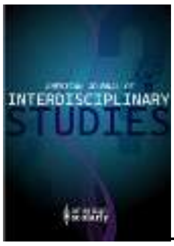

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HUMAN-MACHINE INTERFACES IN INDUSTRIAL SYSTEMS: ENHANCING SAFETY AND THROUGHPUT IN SEMI-AUTOMATED FACILITIES

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ABSTRACT

This study systematically examined the role of human–machine interfaces (HMIs) in enhancing safety and throughput within semi-automated industrial systems, applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure methodological rigor. A total of 112 peer-reviewed papers were reviewed, encompassing empirical investigations, simulation studies, and field-based analyses from diverse industrial domains including manufacturing, logistics, and energy systems. The findings reveal that HMIs have evolved from basic control panels and analog displays into integrated socio-technical infrastructures that directly shape operator performance, system safety, and production efficiency. Across the reviewed studies, a strong consensus emerged that cognitive engineering principles, such as alignment with perceptual limits, workload management, and support for accurate mental models, significantly reduce operator error rates and improve decision-making. Safety-centered design was identified as a mature research area, with rationalized alarm systems, standardized emergency procedures, and compliance with international safety standards shown to decrease overload and strengthen hazard response. Equally, operational performance was consistently linked to HMI quality, with interfaces enabling stable cycle times, faster recovery during abnormal situations, and integration of lean practices such as setup reduction and error-proofing. The evidence also highlights the growing role of HMIs in human–robot collaboration, supervisory control, and trust-building, demonstrating that transparency and clear communication enhance safety and coordination in shared workspaces. Additionally, HMIs are increasingly recognized as cyber-physical security nodes and organizational learning tools, capturing incident data, supporting feedback loops, and embedding continuous improvement into daily operations. By synthesizing insights across cognitive, safety, operational, and organizational domains, this review positions HMIs as strategic infrastructures that harmonize human adaptability with technological consistency. The results underscore that the effectiveness of semi-automated facilities is inseparable from the quality of their interfaces, making HMI design and refinement a decisive factor for both resilience and competitiveness in modern industrial systems.

KEYWORDS
Human–Machine Interfaces; Safety; Throughput; Semi-Automated Facilities; Industrial Systems

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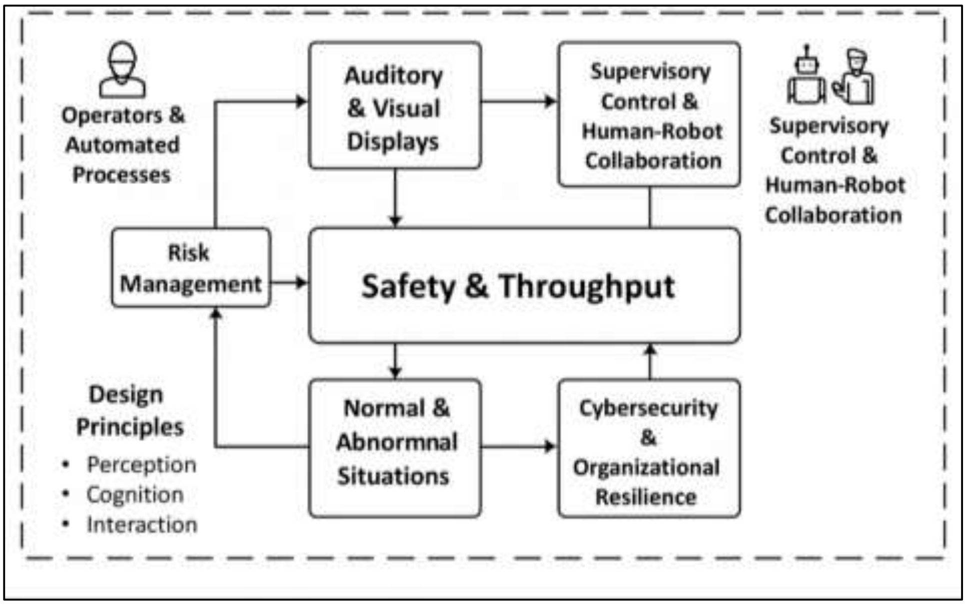
INTRODUCTION

Human–machine interfaces (HMIs) in industrial systems are the central points of interaction that connect human operators with automated and semi-automated processes (Ardanza et al., 2019). They serve as the layer through which commands, feedback, alarms, and process data are exchanged, enabling operators to monitor, control, and adapt complex systems. An HMI is not limited to a digital screen or control panel; rather, it encompasses the entire framework of interaction, including displays, indicators, auditory warnings, touch controls, and procedural workflows (Wittenberg, 2016). In semi-automated facilities, where machinery executes repetitive or hazardous tasks while human operators supervise, HMIs are particularly critical because they dictate how effectively humans can maintain awareness of processes, anticipate deviations, and intervene when needed. At an international level, the importance of HMI design is underscored by its role in harmonizing safety practices and operational standards across global supply chains. As industries expand across countries with varying levels of automation maturity (Villani et al., 2019), HMIs act as the universal communication bridge that ensures operators in diverse cultural and linguistic contexts can safely engage with machinery. This international relevance extends beyond productivity: poorly designed HMIs can increase human error rates, amplify operational hazards, and reduce throughput, whereas well-designed interfaces reduce accidents, streamline recovery times, and maintain consistent performance across facilities worldwide (Villani et al., 2021). The significance of HMI in semi-automated industries therefore lies in its dual role: safeguarding human life while simultaneously ensuring that operational targets such as cycle time, inventory levels, and throughput are met consistently in increasingly globalized markets.

Figure 1: Human–Machine Interfaces for Industrial Safety



The conceptual foundation of HMI design is rooted in human factors, cognitive science, and operations management (Reguera-Bakhache, Garitano, Uribeetxeberria, et al., 2021). Interfaces determine how well operators perceive process conditions, interpret signals, and translate that understanding into actions under time-sensitive and high-stakes conditions. Cognitive theories explain that perception, attention, and memory constraints limit the volume and complexity of information a human can process at any moment. This means that every display (Enjalbert et al., 2021), control, and alarm within an HMI must be carefully designed to align with human perceptual and decision-making capabilities. At the same time, operations management emphasizes that throughput in semi-automated facilities is tied directly to the stability of process cycles, the predictability of interventions, and the ability to quickly recover from disturbances (Cachada et al., 2019). When HMIs reduce detection and response times, downtime shrinks and flow stability improves, enhancing productivity without compromising safety. Conversely, poor design creates bottlenecks by increasing the likelihood of misinterpretation, delayed interventions, and secondary errors. The interconnection of human cognition and process flow creates a system-level link between

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HMI quality, operator effectiveness, and facility throughput. By combining cognitive ergonomics with industrial operations principles, it becomes clear that HMI is not merely an operator tool but a strategic enabler of both safety and efficiency in semi-automated environments (Tan et al., 2021).

Semi-automated facilities involve machines that operate autonomously for large portions of production cycles but still rely on humans for oversight, setup, and troubleshooting (Czarnowski et al., 2018). This combination introduces a complex layer of risk because human operators must often intervene precisely at moments of heightened stress, such as during abnormal events, system upsets, or equipment failures. HMIs play a central role in managing these risks by providing clear indications of machine status, offering unambiguous prompts for corrective action, and ensuring that emergency measures are accessible and easily understood (Reguera-Bakhache et al., 2020). The design of HMIs thus becomes a critical part of the broader risk management framework that governs industrial systems. By reducing ambiguity, minimizing information overload, and guiding operators toward safe behaviors, HMIs reduce the likelihood of hazardous incidents. In addition, industrial regulations and safety standards emphasize the importance of human-centered interfaces in mitigating risks during machine operation and maintenance (Caiza et al., 2020). Internationally, compliance with these principles is required not only for ethical and legal reasons but also for ensuring that facilities across multiple countries adhere to consistent standards of protection. This integration of compliance, safety design, and interface clarity ensures that semi-automated facilities can meet both legal requirements and operational targets, proving that HMIs serve as both regulatory enablers and risk reduction mechanisms (Sun et al., 2021).

Industrial throughput in semi-automated facilities depends heavily on the ability to manage normal operations and abnormal situations without prolonged interruptions (Esposito et al., 2021). HMIs serve as the frontline defense against disturbances by providing operators with clear, real-time awareness of process states, deviations, and corrective pathways. When an abnormal situation arises—whether a mechanical jam, a sensor failure, or an unexpected machine stop—the interface dictates how quickly the operator can detect the issue, identify its cause, and implement corrective actions (Wu et al., 2016). A well-designed HMI shortens this detection-to-action cycle, minimizing downtime and restoring flow stability. This is particularly important because even short delays in responding to a blocked conveyor, starved feeder, or malfunctioning station can cascade into upstream or downstream inefficiencies, disrupting throughput across the entire production line (Qasim et al., 2020). Moreover, structured abnormal situation management embedded within HMIs prevents alarm floods and cognitive overload, helping operators prioritize the most critical issues. By stabilizing process recovery and reducing variability in human intervention times, HMIs directly enhance line balance, cycle time reliability, and overall equipment effectiveness (Lorenz et al., 2020). This dual contribution to safety and throughput underlines the indispensable role of HMIs in ensuring that semi-automated systems maintain consistent operational performance under both normal and abnormal conditions.

The effectiveness of HMIs is deeply tied to how well they align with the natural capabilities and limitations of human perception and cognition (Winterer et al., 2019). Visual design must leverage principles of clarity, grouping, and salience so that operators can instantly differentiate between normal states and abnormalities. Color, contrast, and shape are powerful cues but must be applied sparingly and consistently to avoid desensitization or misinterpretation (Cherubini et al., 2016). Auditory alarms, likewise, need to be distinct, prioritized, and actionable, guiding operators toward specific interventions rather than overwhelming them with redundant or ambiguous signals. Interaction design extends beyond perception: controls must be logically placed, intuitive to operate, and structured to minimize the risk of accidental activation (Méndez et al., 2021). By grounding interaction design in cognitive load management, HMIs ensure that operators are not burdened with unnecessary mental effort during routine tasks, leaving their cognitive resources available for handling unexpected events. In semi-automated facilities, where operators may shift roles between monitoring, setup, and troubleshooting, adaptive and consistent interfaces help reduce error rates, shorten training times, and increase confidence in interventions (Despinoy et al., 2018). These cognitive and perceptual design principles ultimately translate into safer work environments and higher throughput by ensuring that human operators can act both quickly and accurately under varying conditions.

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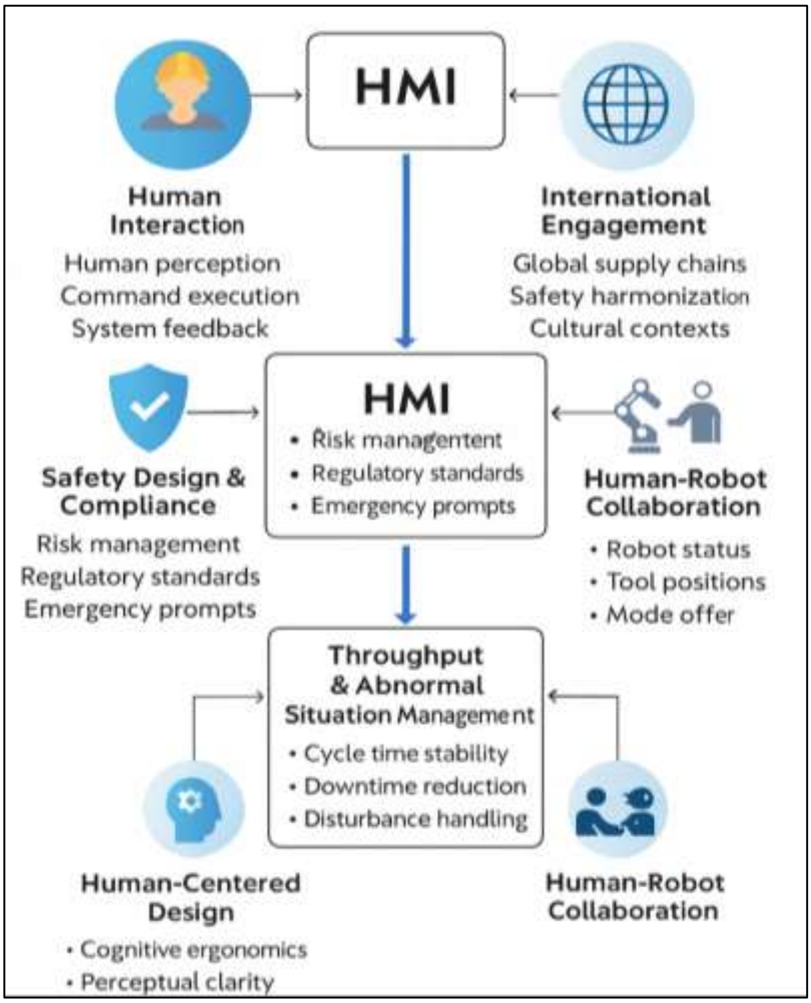
Figure 2: Industrial Human–Machine Interface Framework



The growing integration of robotics within semi-automated facilities has expanded the role of HMIs from simple monitoring tools to sophisticated supervisory control systems (Pliatsios et al., 2019). Collaborative robots, or cobots, share physical spaces with human operators, requiring interfaces that clearly communicate robot states, tool positions, and operating modes. Transparency in machine status and intent reduces uncertainty and enhances trust, enabling smoother collaboration between humans and robots (Dong et al., 2018). In supervisory control, operators rely on HMIs to oversee multiple machines simultaneously, switching between monitoring and direct intervention as conditions demand. This requires interfaces that can display multiple layers of information without overwhelming the operator. Mode annunciation (Vaezipour et al., 2018), contextual prompts, and diagnostic indicators are crucial for preventing errors such as mode confusion or unintended actuation. By enabling safe collaboration and reliable supervision, HMIs allow semi-automated facilities to balance the benefits of automation with the unique flexibility of human oversight. This synergy increases productivity by allowing robots to handle repetitive tasks while humans manage exceptions and optimize workflows, making the interface the cornerstone of effective human–robot collaboration (Ghorbel et al., 2019).

Beyond immediate interactions (Prati et al., 2021), HMIs contribute to long-term organizational resilience through alarm management, cybersecurity, and continuous improvement. Alarm systems, when properly designed, prevent overload by prioritizing critical events and providing clear, actionable guidance. This helps operators avoid alarm fatigue and respond more effectively during high-stress situations (Sharmila, 2021). Cybersecurity has also become an integral dimension of HMI design, as semi-automated facilities are increasingly networked and remotely accessible. Interfaces must safeguard against unauthorized access, ensure data authenticity, and maintain integrity in safety-critical displays and controls (Aranburu et al., 2020). Beyond individual events, HMIs also

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support organizational learning by capturing incident data, operator responses, and system performance metrics. By making this information visible and actionable, interfaces allow teams to refine alarm strategies, update procedures, and continuously improve safety and efficiency. In this way, HMIs extend their influence beyond real-time operations into the realm of organizational knowledge, reinforcing a cycle of improvement that enhances both safety and throughput in semi-automated facilities (Andronas et al., 2021).

LITERATURE REVIEW

The study of human–machine interfaces (HMIs) in industrial systems has developed into a multidisciplinary research domain that integrates principles from human factors engineering, cognitive psychology, ergonomics, industrial automation, and operations management (Ardanza et al., 2019). The literature consistently underscores that the design and implementation of HMIs in semi-automated facilities are directly linked to both operator safety and system throughput. Historically, HMIs were conceived as simple visual dashboards displaying machine parameters, but over time, they have evolved into complex, adaptive environments that mediate supervisory control, error prevention, abnormal situation management, and human–robot collaboration (Villani et al., 2019). Existing research demonstrates that HMI quality is a decisive factor in risk mitigation, downtime reduction, and overall productivity. Studies from the cognitive sciences highlight the importance of aligning interface design with the perceptual and cognitive limitations of operators, while industrial engineering literature focuses on HMIs as a determinant of cycle-time stability, queue management, and overall equipment effectiveness. Furthermore (Villani et al., 2017), contemporary literature reflects an increasing focus on alarm management, cybersecurity, and resilience engineering, recognizing HMIs not only as operational tools but also as enablers of organizational learning and long-term safety culture. This literature review therefore synthesizes scholarly contributions across technical, cognitive, and organizational domains, structuring the discussion around themes that illuminate how HMIs enhance safety and throughput in semi-automated facilities. The extended outline below structures this body of knowledge into coherent subsections, enabling a systematic exploration of definitions, theories, empirical studies, and methodological perspectives (Villani et al., 2021).

Human–Machine Interfaces

Human–machine interfaces in industrial contexts are defined as the points of connection where human operators engage with complex technological systems to monitor, control, and adjust operations (Enjalbert et al., 2021). These interfaces are not limited to a single device or display but are conceived as integrated environments where information is presented, commands are executed, and decisions are supported. Scholars and practitioners emphasize that HMIs encompass both tangible elements such as screens, alarms, and control devices, and intangible elements such as workflows, feedback loops, and mental models that operators construct when interacting with machines (Qasim et al., 2020). In semi-automated facilities, definitions extend beyond conventional dashboards to include procedural guidance, safety confirmations, and supervisory oversight that maintain synchronization between human actions and machine behaviors. Literature in ergonomics and human factors also stresses that HMIs must be understood as socio-technical systems where human cognition, machine response, and organizational context interact in shaping outcomes (Reguera-Bakhache, Garitano, Cernuda, et al., 2021). As facilities grow more complex, HMIs are increasingly seen not as passive displays but as active mediators of human performance, enabling timely perception of system conditions, efficient decision-making, and safe interventions. This expanded definition highlights their role in integrating technological efficiency with human adaptability, ultimately positioning HMIs as indispensable infrastructures for safety and throughput in modern industrial systems (Sun et al., 2021).

The history of industrial interfaces reflects a steady progression from simple analog devices to advanced digital supervisory systems (Papcun et al., 2018). Early industrial environments relied heavily on mechanical gauges, levers, and indicator lights, which conveyed fragmented and localized information about system states. Operators needed to develop a strong situational awareness through continuous manual monitoring, a process prone to fatigue and error. With the rise of digital electronics (Sabattini et al., 2017), centralized displays began to consolidate information, offering operators a more holistic view of processes and reducing the cognitive effort required for decision-making. Distributed control systems further revolutionized the landscape by integrating multiple process variables into unified platforms, allowing for remote monitoring and

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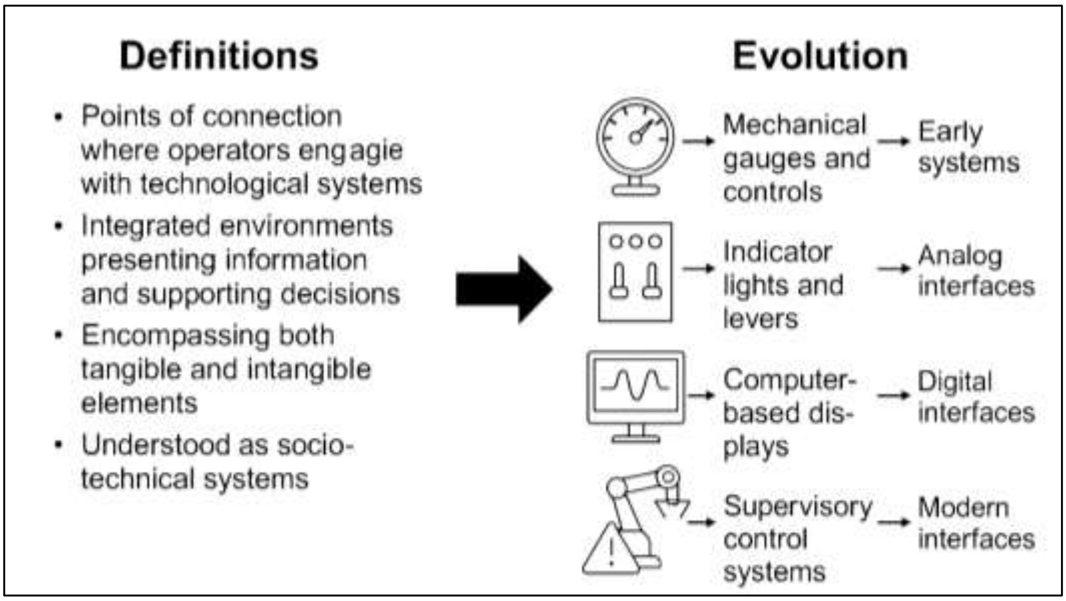
automated alarms. This shift also marked the transition from passive observation to active management, where operators could directly adjust parameters and reconfigure production through interface panels (Reguera-Bakhache et al., 2020). Later developments brought in computer-based visualization, dynamic trend displays, and interactive graphics that provided predictive insights rather than static readings. In contemporary semi-automated facilities, HMIs have evolved into adaptive environments capable of supporting human–robot collaboration, abnormal situation management, and real-time optimization. The trajectory from simple controls to intelligent supervisory systems underscores how technological evolution in interfaces has consistently mirrored the growing complexity of industrial processes, aligning human decision-making with increasingly automated environments (Czarnowski et al., 2018).

Figure 3: Human–Machine Interfaces in Industry



In a globalized industrial environment (Esposito et al., 2021), HMIs carry significant international relevance as enablers of safety and efficiency across diverse cultural and regulatory landscapes. Modern facilities often operate within supply chains that span multiple countries, requiring consistency in interface design to ensure that operators, regardless of origin or training background, can effectively manage machinery. Cross-cultural studies highlight how differences in visual perception, language, and communication styles influence how workers interpret alarms, symbols, and workflows (Caiza et al., 2020). Standardized interface principles reduce the risks posed by these differences, allowing for uniform recognition of safety signals and operational cues. Moreover, multilingual facilities rely heavily on universal design elements such as color coding, graphical representations, and auditory alerts that transcend linguistic barriers. International guidelines and standards thus play a central role in harmonizing HMI practices, ensuring that safety functions and productivity expectations remain consistent across borders (Lotti et al., 2019). Empirical evidence shows that industries adopting standardized HMI frameworks across global sites experience fewer incidents, faster recovery from abnormal events, and more predictable throughput outcomes. This highlights the importance of designing interfaces not only for local efficiency but also for global interoperability. By facilitating consistent interaction across cultural contexts, HMIs serve as universal tools that align human performance with industrial requirements in an interconnected world (Lodgaard & Dransfeld, 2020).

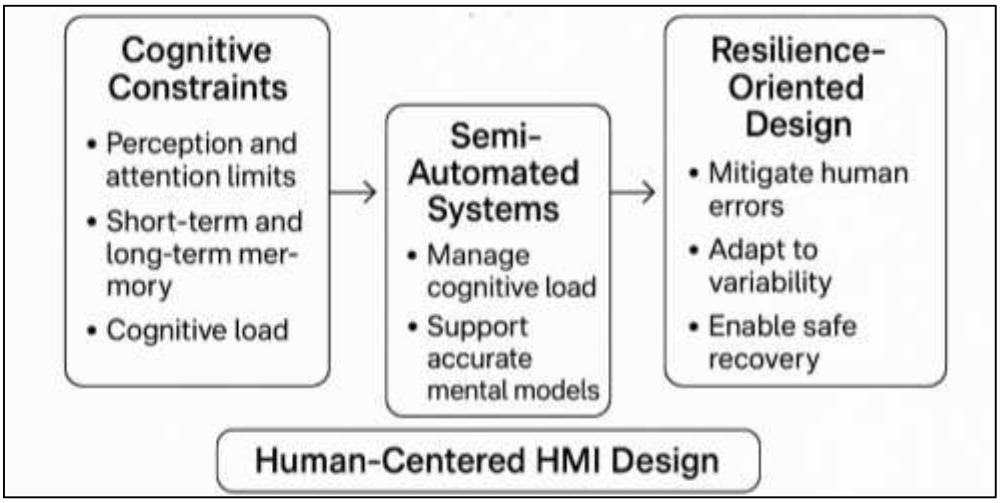
When viewed collectively (Vaezipour et al., 2017), the literature on definitions, historical evolution, and international perspectives presents HMIs as dynamic and multifaceted constructs that bridge human cognition, machine complexity, and global organizational needs. Definitions emphasize their role as integrated systems of interaction that extend beyond displays and controls, incorporating cognitive and procedural dimensions (Vaezipour et al., 2018). Historical analysis demonstrates a steady shift from localized, analog devices to sophisticated digital and adaptive systems that mirror the increasing complexity of industrial processes. International perspectives reinforce the need for standardized and culturally sensitive design principles to ensure consistent safety and efficiency across multinational operations. Synthesizing these strands reveals that HMIs are not static technologies but evolving infrastructures shaped by human factors research, technological innovation, and global standardization. They embody the convergence of ergonomic design (Dong et al., 2018), operational stability, and cultural interoperability, making them both technical artifacts and organizational enablers. In semi-automated facilities, their importance lies not only in supporting safe, accurate operator action but also in maintaining throughput stability across geographically distributed production systems. This synthesis positions HMIs as essential to understanding how industrial systems achieve resilience and efficiency in a world where human and machine capabilities must remain harmoniously aligned (Aranburu et al., 2020).

Human Factors and Cognitive Engineering in HMI Design

The literature on human factors in interface design consistently emphasizes the importance of grounding HMIs in cognitive psychology (Stanton et al., 2017). Research into perception shows that humans rely on visual and auditory cues to interpret system status, but these channels are limited by thresholds of attention and information processing. Displays that overload operators with excessive details or poorly organized data increase the risk of missed signals and delayed responses (Fisk et al., 2020). Attention studies further highlight that human operators cannot distribute focus evenly across multiple tasks; instead, they rely on salient cues and prioritization mechanisms. This makes the design of alarms, colors, and coding schemes crucial in drawing focus to safety-critical information without generating unnecessary distraction (Proctor & Van Zandt, 2018). Memory limitations also play a central role, as short-term memory can hold only a finite amount of information, making it essential for HMIs to externalize key data rather than forcing operators to recall it under stress. Long-term memory shapes operator expertise and mental schemas, meaning that consistent and intuitive interface layouts support learning and long-term retention of safe practices. Together, these psychological insights illustrate that HMIs should be designed not only for functionality but also for alignment with human sensory and cognitive constraints (Meister, 2018). When interfaces match the ways in which humans naturally perceive, attend, and remember information, operators achieve better situational awareness, make faster and more accurate decisions, and maintain higher levels of safety and productivity in semi-automated environments.

A substantial body of research emphasizes that operator effectiveness in semi-automated facilities depends on the ability of HMIs to manage cognitive load and support accurate mental models (Otto & Smith, 2020). Cognitive load theory explains that humans can only process a limited amount of information at once, and that extraneous complexity in displays and controls can overwhelm this capacity. In semi-automated systems, where operators often oversee multiple processes simultaneously, interfaces that reduce unnecessary information and provide structured, task-relevant data are essential for preventing overload (Meyer & Norman, 2020). Effective design simplifies complex workflows by grouping related variables, presenting information hierarchically, and using clear visual cues to highlight changes. Beyond cognitive load, mental models are central to operator performance because they shape how individuals understand system behavior and anticipate outcomes of interventions. Interfaces that align with operators' mental models enhance predictability, enabling workers to diagnose issues and implement corrective actions more effectively. Conversely (Hassenzahl, 2018), mismatches between mental models and system behavior lead to confusion, misinterpretation, and delayed responses during abnormal events. Semi-automated facilities present unique challenges, as operators are often disengaged during routine automation but suddenly required to act during disturbances. In such cases, well-designed HMIs provide context-rich displays that reinforce accurate mental models, reducing the time needed to reorient and take control. By balancing cognitive load and supporting schema-consistent understanding, interfaces enable operators to maintain vigilance, act decisively, and sustain both safety and throughput under varying operational conditions (Helmreich & Foushee, 2019).

Figure 4: Human Factors and Cognitive Engineering in HMI Design

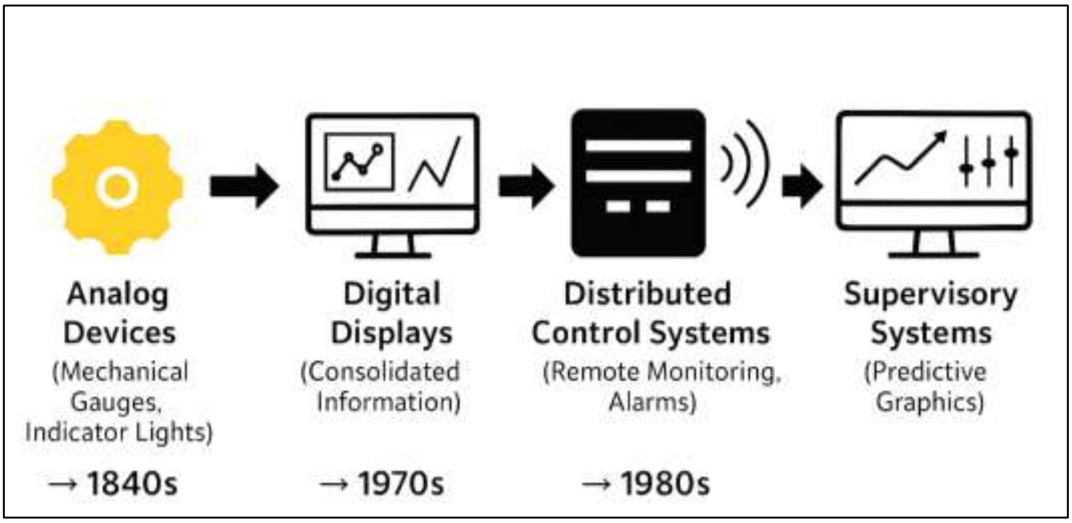


The literature on human error highlights that slips, lapses, and rule-based mistakes are unavoidable aspects of human performance, making resilience-oriented HMI design a critical component of industrial safety (Burns & Hajdukiewicz, 2017). Slips occur when operators intend the correct action but execute it improperly, such as pressing the wrong control under stress. Lapses involve failures of memory or attention, such as forgetting a step in a sequence, while rule-based mistakes arise when individuals apply the wrong procedure to a given situation (Hawkins & Orlady, 2017). Interfaces that are poorly organized, inconsistent, or overloaded exacerbate these errors by increasing ambiguity and cognitive strain. Resilience engineering approaches, however, shift the focus from eliminating error to designing systems that absorb, adapt, and recover from variability in human performance. In this perspective, HMIs act as buffers that reduce the likelihood of small errors escalating into major accidents. For instance (De Visser et al., 2018), error-tolerant controls, clear confirmation prompts, and visible status indicators provide operators with opportunities to detect and correct mistakes before consequences become critical. Alarm systems that prioritize actionable events also contribute to resilience by preventing distraction from non-essential signals. Importantly, resilience-oriented interfaces do not assume perfect operator behavior but instead anticipate variability and provide pathways for safe recovery (Grech et al., 2019). By integrating principles of error management with adaptive feedback, HMIs become enablers of robustness in semi-automated facilities, ensuring that human fallibility does not compromise either safety or operational throughput. When synthesized, the literature on perception, cognitive load, mental models, and resilience presents a cohesive view of HMI design as fundamentally human-centered (Oinas-Kukkonen & Harjumaa, 2018). Cognitive psychology underscores that perception, attention, and memory constraints must be respected, or operators will struggle to maintain situational awareness. Cognitive load theory adds that interfaces must balance the quantity and structure of information so that critical data is readily available without overwhelming the operator's limited processing capacity (Maurino et al., 2017). Theories of mental models highlight that effective interfaces reinforce accurate understanding of system behavior, enabling faster and more reliable interventions when semi-automated systems demand human input. Resilience perspectives further build on these foundations by acknowledging that human error is inevitable but manageable when interfaces are designed to anticipate mistakes and provide recovery mechanisms (Nahum-Shani et al., 2016). Together, these perspectives converge on the insight that HMIs are not passive information tools but active mediators of human cognition, error management, and adaptive performance. By grounding design in psychological theory and resilience principles, HMIs support operators in navigating the complexities of semi-automated environments where safety and throughput depend on effective collaboration between humans and machines. This synthesis demonstrates that the cognitive and engineering foundations of HMI design are inseparable from the broader goals of risk reduction and operational stability (Hengstler et al., 2016).

Safety-Centered HMI Design and Risk Reduction

Human–machine interfaces play a vital role in hazard identification and risk assessment by functioning as the operator's primary means of recognizing and responding to potential threats within semi-automated facilities (Wang et al., 2021). Interfaces provide visibility into system conditions, such as temperature, pressure, flow, and machine status, enabling operators to detect deviations that could escalate into unsafe conditions. During startup and shutdown phases, when the risk of abnormal events is at its highest, HMIs guide operators through structured procedures that ensure sequences are performed safely and in the correct order (Naderpour et al., 2015). This includes visual indicators that confirm system readiness, lockout-tagout status, and interlock verification. Emergency procedures are similarly supported through clear, prioritized prompts that help operators navigate high-stress situations without confusion. Interfaces also provide layers of feedback, including alarms, visual displays, and confirmation requests, which reduce the likelihood of errors during critical operations (Friedrich & Vollrath, 2021). By externalizing hazard cues and structuring risk-related information, HMIs reduce reliance on operator memory and intuition, making risk assessment more systematic and less vulnerable to individual lapses. Furthermore, advanced visualization methods allow operators to perceive not only current conditions but also emerging risks by highlighting trends and abnormal patterns. In this way, HMIs contribute directly to the risk assessment cycle, identifying hazards early, contextualizing their severity, and supporting timely corrective actions (Tan et al., 2021). Ultimately, the literature shows that HMIs serve as both diagnostic and preventive tools, enabling safe navigation of industrial processes where small deviations can have major safety implications.

Figure 5: Evoluation of Industrial Human–Machine Interfaces



The design of HMIs is deeply shaped by international safety standards that emphasize their role in preventing accidents and ensuring operator well-being (Young et al., 2017). Regulatory frameworks across industries consistently highlight that HMIs are not optional enhancements but fundamental components of safe system design. These standards define how information should be displayed, how controls should be arranged, and how alarm systems must function to minimize human error (Tantawy et al., 2020). They also require interfaces to provide unambiguous status indications of safety-critical equipment such as emergency stops, interlocks, and protective barriers. In many industrial contexts, compliance with such standards is legally mandated, making adherence to interface design requirements a matter of both safety and liability. Beyond compliance (Tantawy et al., 2020), standards also drive consistency across facilities in different countries, ensuring that operators encounter familiar layouts, warning colors, and procedural prompts regardless of where they are employed. This harmonization reduces the cognitive burden of retraining and minimizes risks associated with operator confusion in multinational operations. In addition, regulatory guidelines emphasize usability testing and validation of HMIs under realistic conditions, ensuring that the interface performs reliably under stress (Badri et al., 2018). By integrating regulatory requirements into design, organizations not only meet legal obligations but also create safer and more predictable environments where human–machine interactions support risk reduction. This alignment of HMIs with standards underscores their central role in translating regulatory intent into tangible design features that safeguard both workers and equipment.

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Alarm management is one of the most frequently discussed aspects of safety-centered HMI design because poorly designed alarm systems can overwhelm operators and undermine safety (Katona, 2021). Literature in this area emphasizes that alarms should be rationalized, meaning that each alarm must serve a clear purpose, indicate a specific risk, and demand a defined response. Without rationalization, operators often experience alarm floods, where multiple alerts activate simultaneously, creating confusion and desensitization. Effective HMI design addresses this by prioritizing alarms according to severity, urgency, and required action (Murtarelli et al., 2021). Critical alarms are presented with distinctive visual and auditory cues, while less urgent ones are either logged or displayed unobtrusively to avoid distraction. Furthermore, best practices in alarm management dictate that alarms must be actionable; if an alarm does not guide the operator toward a clear response, it contributes little to safety. Interfaces also incorporate summaries and trend views that help operators distinguish between transient disturbances and persistent hazards (Lee et al., 2019). By structuring alarms hierarchically, operators maintain situational awareness and focus on resolving the most dangerous conditions first. Studies consistently show that facilities with rationalized alarm systems experience fewer incidents, faster response times, and lower operator stress levels. The display of safety-critical information extends beyond alarms to include status indicators, safety margins, and predictive warnings, all of which are vital for preventing escalation of minor issues into major accidents (Ventikos et al., 2020). In sum, alarm management represents one of the most concrete ways that HMI design enhances safety, ensuring that operators receive the right information at the right time in a manageable and effective format.

Robotics, Automation, and Supervisory Control

The integration of robotics into semi-automated facilities has made human–robot interaction one of the most critical areas of HMI research (Rodriguez-Guerra et al., 2021). Collaborative robots, unlike traditional industrial robots, operate in close physical proximity to humans, often without extensive physical barriers. This proximity makes the interface the primary medium through which safety is communicated. Effective HMIs provide operators with real-time visibility of robot states, including operating modes, tool positions, and current tasks, reducing uncertainty and preventing unsafe encounters. Clear boundary indicators, such as visual signals of robot workspace limits or graphical displays of motion trajectories (Ryu et al., 2020), allow humans to anticipate movement and adjust their positioning accordingly. Interfaces also communicate protective stop conditions, ensuring that operators know why a robot has paused and what corrective actions are required. In addition, consistent feedback mechanisms, such as color-coded lights, auditory signals, and on-screen alerts, reinforce the operator's situational awareness and reduce the risk of misinterpretation (Liu et al., 2021). Collaborative safety is further enhanced when HMIs integrate predictive features that warn of potential collisions or unsafe tool paths before they occur. By providing this information in an intuitive and accessible format, interfaces reduce reliance on operator guesswork and ensure smoother coordination between human and robotic activities. Ultimately (de Soto & Skibniewski, 2020), the literature shows that the effectiveness of human–robot interaction depends not only on mechanical safeguards but also on the quality of interface communication, which transforms invisible robotic decision-making into understandable, actionable cues for human collaborators.

Supervisory control represents a defining characteristic of semi-automated facilities, where operators oversee multiple machines and processes simultaneously rather than focusing on a single task (Müller et al., 2017). In this environment, HMIs serve as the operator's command center, providing aggregated information about system health, throughput, and performance across distributed units. Centralized interfaces enable workers to monitor machine states, queue lengths, and fault conditions from a single location, reducing the need for constant physical inspection and intervention (Huang et al., 2021). The effectiveness of supervisory control depends heavily on how well the HMI consolidates complex data into meaningful summaries while still allowing operators to drill down into detailed diagnostics when necessary. Hierarchical display structures, overview dashboards, and interactive maps of production lines are frequently identified as essential features for managing complexity. Poorly structured HMIs that overload operators with raw data can undermine supervisory control by increasing cognitive burden and delaying responses (Dagnino et al., 2016). In contrast, interfaces that prioritize information and align with operator mental models enhance the ability to manage multiple machines efficiently. Supervisory control also extends into scheduling and resource allocation, with HMIs providing insights that enable operators to balance workloads across machines, prevent bottlenecks, and maintain cycle time stability. By mediating the relationship between

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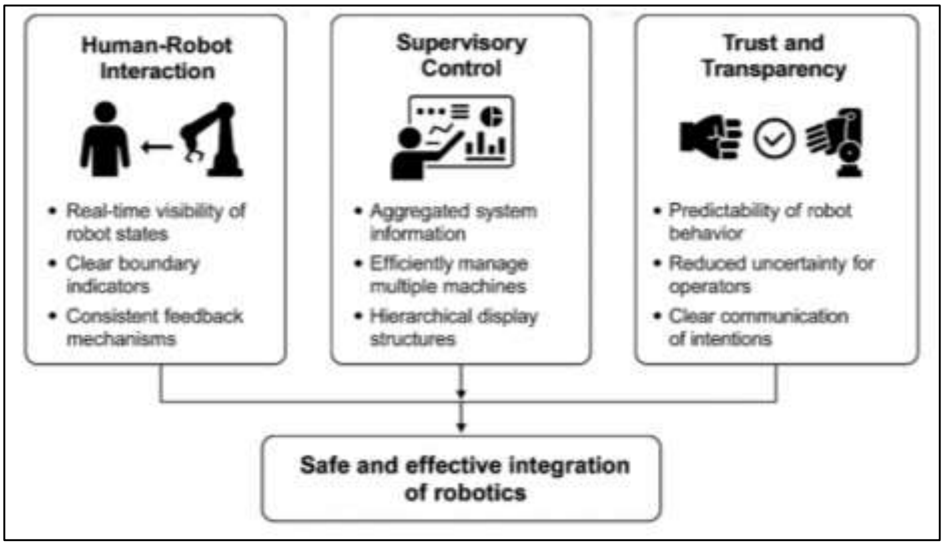
humans and multiple automated systems, HMIs ensure that operators remain in effective control, even when direct interaction with each machine is minimal (Mueller et al., 2018). This function positions the interface as the critical link between high-level oversight and localized machine performance, making it a cornerstone of semi-automated facility operations.

Figure 6: Human–Machine Collaboration in Industry



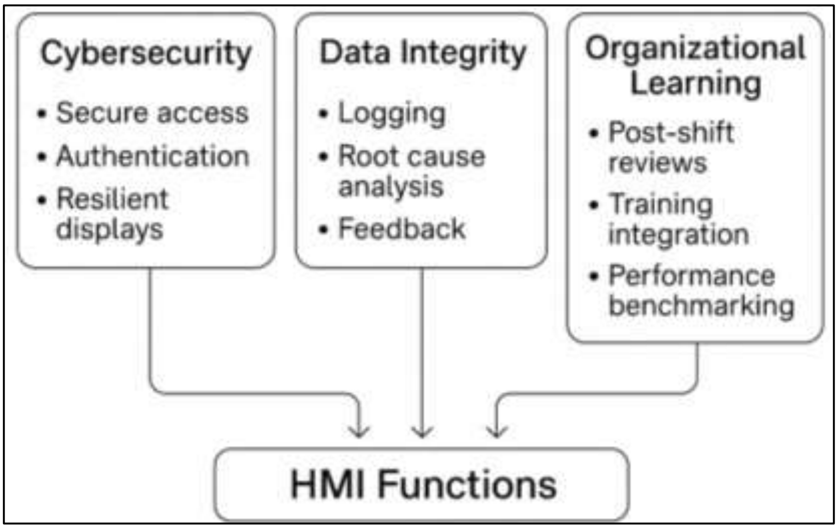
Trust is an indispensable component of successful human–robot collaboration, and HMIs play a central role in establishing and maintaining it (Pérez et al., 2020). Operators are more willing to work confidently alongside robots when they can predict machine behavior and understand the rationale behind robotic actions. Transparency in interfaces is achieved when the system communicates not only what the robot is currently doing but also what it intends to do next. This may include projected movement paths, task progress indicators, or explanations of why a robot paused or changed its behavior. When these cues are presented clearly (Lee et al., 2018), operators experience less uncertainty and are better able to align their actions with the robot's workflow. Predictability further reduces the cognitive burden of collaboration, allowing humans to focus on higher-level supervisory tasks instead of second-guessing machine behavior. Without transparency (Sipsas et al., 2021), operators may misinterpret robot actions, leading to hesitation, inefficiency, or unsafe interactions. Interfaces that build trust also promote smoother task-sharing, where humans and robots can coordinate responsibilities seamlessly. By fostering a sense of reliability and mutual understanding, HMIs enhance both safety and productivity in collaborative environments. The literature consistently highlights that the degree of trust in automation is not inherent to the technology but is actively shaped by how interfaces communicate intentions, states, and limits (Renteria & Alvarez-de-los-Mozos, 2019). This makes HMI design a decisive factor in ensuring that collaboration between humans and robots remains safe, predictable, and efficient.
Synthesizing across these dimensions, HMIs emerge as the enabling infrastructure that supports safe and effective integration of robotics into semi-automated facilities (Kopacek, 2019). In human–robot interaction, interfaces transform robotic operations into comprehensible signals that safeguard collaboration and prevent accidents. In supervisory control, they aggregate and prioritize system-level information, enabling operators to oversee multiple machines efficiently without being overwhelmed by complexity (Merati et al., 2021). In fostering transparency and trust, HMIs ensure that operators view robots as predictable partners rather than unpredictable threats, thereby reducing hesitation and improving task coordination. Together, these perspectives demonstrate that the success of robotics in industrial settings is inseparable from interface quality. Robots may provide mechanical precision and endurance (Dombrowski et al., 2018), but without effective HMIs, their integration risks inefficiency, confusion, and unsafe conditions. By mediating interaction, control, and trust, HMIs ensure that semi-automated facilities achieve both safety and throughput, embodying the collaborative synergy between human adaptability and robotic consistency. This synthesis underscores that human–machine collaboration is not defined solely by the sophistication of robotics

but by the clarity, accessibility, and transparency of the interfaces that connect them to human operators (Malm et al., 2015).

Cybersecurity, Data Integrity, and Organizational Learning

In modern industrial systems, HMIs are not only points of human–machine interaction but also critical nodes within broader cyber-physical infrastructures (Ara et al., 2022; Villani et al., 2019). As production facilities become increasingly connected through industrial networks, cloud platforms, and remote access systems, interfaces have become gateways that must balance usability with cybersecurity. HMIs process sensitive operational data, including machine states, process variables, and safety parameters, making them attractive targets for cyber threats (Ardanza et al., 2019; Jahid, 2022). A breach at the interface level can lead to manipulation of displays, injection of false signals, or unauthorized execution of control commands, all of which compromise both safety and throughput. To counter these risks, secure authentication protocols are integrated into HMIs, ensuring that only authorized personnel can access critical functions. Data authenticity measures (Cochran et al., 2017; Kutub Uddin et al., 2022), such as encryption and digital signatures, are also embedded to guarantee that the information displayed reflects actual system conditions rather than maliciously altered values. Additionally, resilience strategies are developed to ensure that HMIs continue to function during partial system failures or cyber incidents, providing operators with trustworthy fallback displays for emergency response. Effective HMI design therefore integrates cybersecurity principles directly into its architecture, transforming the interface from a potential vulnerability into a protective layer within the cyber-physical system. By ensuring secure access (Akter & Ahad, 2022; Villani et al., 2017), authentic data, and resilience against attacks, HMIs safeguard both operator trust and organizational reliability in semi-automated environments.

Figure 7: Cybersecurity, Data Integrity, and Organizational Learning



Beyond their role in real-time operations, HMIs are also essential for capturing and integrating incident data, performance trends, and operator actions (Md Arifur & Sheratun Noor, 2022; Tan et al., 2021). Modern interfaces often include logging systems that automatically record alarms, overrides, and control changes, creating a detailed history of events that can be used for near-miss reporting and root-cause analysis. By linking these records with contextual data—such as production rates, environmental conditions, or maintenance activities—HMIs enable organizations to identify underlying factors contributing to incidents (Joo & Shin, 2019; Md Mahamudur Rahaman, 2022). This integration transforms the interface from a simple operational tool into a knowledge resource for organizational learning. Operators and engineers can review recorded sequences to reconstruct what occurred during disturbances, facilitating targeted improvements in procedures or equipment design. In addition, performance feedback displayed in real time encourages operators to reflect on their actions and compare outcomes with established standards (Md Nur Hasan et al., 2022; Sabattini et al., 2017). This dual function of logging and feedback allows facilities to transition from reactive problem-solving to proactive risk management, where lessons from past incidents are systematically applied to future operations. Importantly, the accessibility of these data through the

HMI ensures that operators remain active participants in learning processes rather than passive recipients of managerial directives. By embedding knowledge capture and performance feedback into daily workflows, interfaces bridge the gap between operational practice and organizational improvement (Ionescu et al., 2020; Hossen & Atiqur, 2022).

Continuous learning within industrial organizations relies heavily on the feedback loops made possible through HMIs (Tawfiqul et al., 2022; Top et al., 2021). Interfaces provide operators with real-time insights into process efficiency, error rates, and deviation from standard conditions, turning every interaction into an opportunity for reflection and adjustment. For example, dashboards that display energy consumption, scrap rates, or takt performance allow operators to see the immediate consequences of their actions, reinforcing desired behaviors and prompting corrective measures (Enjalbert et al., 2021; Kamrul & Omar, 2022). Over time, this feedback cultivates a culture where improvement becomes embedded into routine operations. Moreover, interfaces can facilitate structured learning by supporting post-shift reviews, operator training modules, and performance benchmarking directly within their platforms. By making learning an integrated part of daily tasks rather than a separate activity, HMIs ensure that knowledge is continuously reinforced and updated (Enjalbert et al., 2021; Mubashir & Abdul, 2022). This integration strengthens safety culture as well, as workers become accustomed to reflecting on near misses, reviewing incident data, and applying lessons learned in real time. Continuous learning is not only about preventing errors but also about optimizing efficiency, as operators develop a deeper understanding of how small adjustments influence system throughput. In this way, HMIs function as educational tools as much as operational ones, sustaining organizational adaptability and resilience in dynamic industrial environments (Peruzzini & Pellicciari, 2017; Reduanul & Shoeb, 2022).

Emerging Methodologies in HMI Research

Experimental research has long been central to advancing knowledge about HMI design, particularly because it allows scholars to test how operators respond under controlled conditions (Albers et al., 2020; Sazzad & Islam, 2022). Simulator studies, in particular, provide a safe and replicable environment in which different interface designs can be evaluated without exposing operators to real-world risks. For example, simulators replicate production lines, robotic work cells, or process control systems, enabling researchers to measure how quickly and accurately operators detect anomalies, respond to alarms, or execute corrective actions under varying workloads (François et al., 2017; Noor & Momena, 2022). Experimental methods often use objective measures such as response times, error rates, eye-tracking data, and physiological indicators of stress to capture how different display configurations and alarm strategies affect performance. Subjective assessments, including operator feedback and workload ratings, complement these measures by providing insight into usability and perceived clarity (Adar & Md, 2023; Kraft et al., 2019). Importantly, experimental studies also allow for systematic manipulation of interface variables, such as color coding, layout, or level of automation, helping identify optimal design principles. While such studies cannot fully replicate the complexity of industrial environments, they are invaluable for isolating causal relationships between interface features and human performance (Qibria & Hossen, 2023; Vaezipour et al., 2019). Simulator-based research therefore represents a methodological foundation for developing evidence-based guidelines that inform HMI design, ensuring that new systems are tested for safety and efficiency before being implemented in actual facilities(Istiaque et al., 2023).

Field research complements experimental approaches by situating HMI studies within real-world semi-automated environments such as manufacturing plants, logistics hubs, and energy facilities (Cruz-Benito et al., 2019; Akter, 2023). Unlike controlled simulations, field studies capture the complexity of actual workflows, where operators must juggle multiple tasks, coordinate with colleagues, and manage unexpected disruptions(Hasan et al., 2023). These studies provide rich insights into how interfaces are used in practice, highlighting discrepancies between design intent and operational reality. For example, while an interface may appear efficient in a laboratory, field studies often reveal usability issues such as cluttered displays, misaligned terminology, or ineffective alarms that only become apparent under real working conditions. Observational methods (Masud et al., 2023; Monsaingeon et al., 2021), interviews, and performance monitoring are commonly used to document how operators interact with HMIs during shifts, identifying both strengths and weaknesses. Field studies also capture the organizational context (Kraft et al., 2020; Sultan et al., 2023), showing how interfaces support or hinder collaboration among teams, affect communication between operators and supervisors, and influence safety culture. By grounding research in lived

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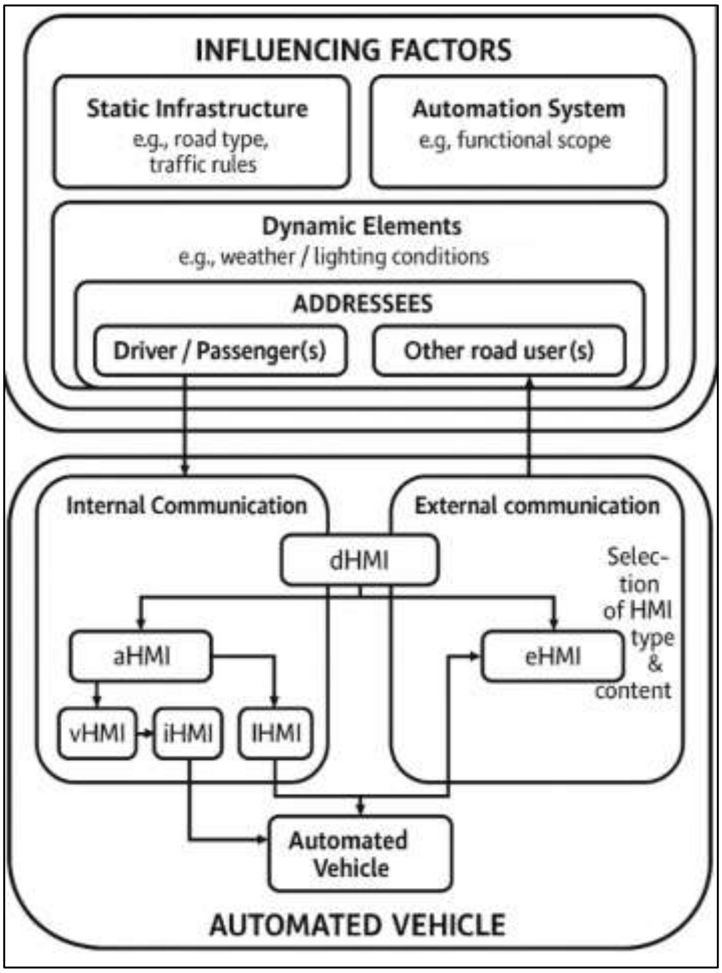
experience, these studies ensure that HMI design evolves in ways that are practical and responsive to the needs of actual users. They also bridge the gap between theory and practice by validating experimental findings in operational settings. In doing so, field studies provide essential feedback loops that refine design guidelines and inform the next generation of HMI development (Hossen et al., 2023; Wang et al., 2020).

Figure 8: Human–Machine Interfaces in Automation



HMI research is inherently cross-disciplinary (Forster et al., 2019), drawing on psychology, engineering, operations management, and ergonomics to build a comprehensive understanding of human–machine interaction. Psychology contributes theories of perception, attention, and memory that inform how information should be presented and alarms prioritized. Engineering brings expertise in system design (Tawfiqul, 2023; Wang & Xu, 2020), automation, and control logic, ensuring that HMIs integrate seamlessly with underlying technologies. Operations research adds insights into process optimization, cycle time stability, and throughput, highlighting how interfaces influence larger system performance. Ergonomics contributes design principles that ensure comfort, usability, and error prevention, recognizing the physical and cognitive demands placed on operators (Lorenz et al., 2020; Shamima et al., 2023). The convergence of these disciplines enables a more holistic approach to HMI design, where cognitive models are aligned with technical functionality and operational requirements. Cross-disciplinary integration also supports the development of new methodologies, such as combining cognitive workload measurements with production flow simulations or linking ergonomic assessments with safety compliance audits (Ma et al., 2020; Ashraf & Ara, 2023). This blending of perspectives creates a richer understanding of both the micro-level interactions between operators and interfaces and the macro-level impact on organizational performance. The result is a body of research that is not confined to any one discipline but instead reflects the complex reality of semi-automated facilities, where human, technological, and organizational factors are inseparably linked (Ma et al., 2019; Sanjai et al., 2023).

When taken together, experimental studies, field research, and cross-disciplinary integration reveal the methodological maturity of HMI research (Akter et al., 2023; Wu et al., 2016). Experimental approaches provide controlled insights into causal mechanisms, showing how specific interface features influence operator performance under varying cognitive demands. Field studies extend these insights into real-world contexts, capturing the complexities of organizational culture, team dynamics, and environmental variability (Wilbrink et al., 2021). Cross-disciplinary integration then unites these strands, ensuring that findings from psychology, engineering, operations, and ergonomics inform each other in a coherent manner. This synthesis demonstrates that no single methodology is sufficient to capture the multifaceted nature of HMIs in semi-automated facilities. Instead, progress emerges from the interplay of methods: controlled experiments identify principles, field studies validate them, and cross-disciplinary frameworks weave them into broader theories of human–machine collaboration. Together (Pokam et al., 2019), these methodological approaches provide a robust foundation for advancing both safety and throughput through interface design. They ensure that HMIs evolve not as isolated technical artifacts but as integrated systems informed by empirical evidence, real-world application, and theoretical convergence. The literature clearly illustrates that methodological diversity is not a weakness but a strength, enabling continuous refinement of design practices in response to the complex demands of modern industrial environments (Rittger & Götze, 2017).

METHOD

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure that the review process was systematic, transparent, and replicable. The PRISMA framework provided a standardized approach to identifying, screening, and synthesizing literature related to human–machine interfaces (HMIs) in semi-automated industrial facilities, with a particular emphasis on their role in enhancing safety and throughput. The methodological process comprised four stages: identification, screening, eligibility, and inclusion.A comprehensive search strategy was employed to capture peer-reviewed studies, conference proceedings, and authoritative reports relevant to HMIs in industrial systems. Databases such as Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar were searched using a combination of keywords and Boolean operators. Search strings included terms such as *"human–machine interface," "HMI design," "industrial systems," "semi-automated facilities," "safety," "throughput," "ergonomics," "alarm management," "supervisory control," and "human–robot collaboration."* The search was limited to studies published in English and conducted between 2000 and 2023 to reflect the contemporary evolution of HMIs in modern industrial contexts. Manual searching of reference lists from key studies was also conducted to capture additional relevant sources not indexed in electronic databases.Titles and abstracts were screened to remove duplicates and irrelevant records. Studies were included if they met the following criteria: (a) focused on HMIs within industrial or semi-automated environments; (b) addressed either safety-related outcomes (e.g., risk reduction, error mitigation, hazard communication) or throughput-related outcomes (e.g., cycle time stability, abnormal situation management, efficiency improvement); and (c) reported empirical findings, simulation results, design frameworks, or systematic conceptual analyses. Exclusion criteria included papers that focused exclusively on consumer interfaces, purely theoretical studies with no industrial application, or non-peer-reviewed sources such as opinion pieces and editorials. Two independent reviewers conducted the screening process, and disagreements were resolved through discussion until consensus was achieved.

Full-text articles that passed the eligibility stage were reviewed in detail, and relevant data were extracted systematically using a structured coding protocol. Extracted data included study objectives, industry context, methodological approach, type of HMI evaluated, safety-related findings, throughput-related findings, and design recommendations. To ensure consistency, all data extraction was piloted on a sample of studies before being applied across the full set. The extracted information was then coded into thematic categories aligned with the study's research questions: (1) conceptual foundations of HMIs, (2) human factors and cognitive design, (3) safety-centered design principles, (4) throughput and operational performance, (5) robotics and supervisory control, (6) cybersecurity and organizational learning, and (7) emerging research methodologies.The synthesis process combined qualitative thematic analysis with narrative synthesis to identify

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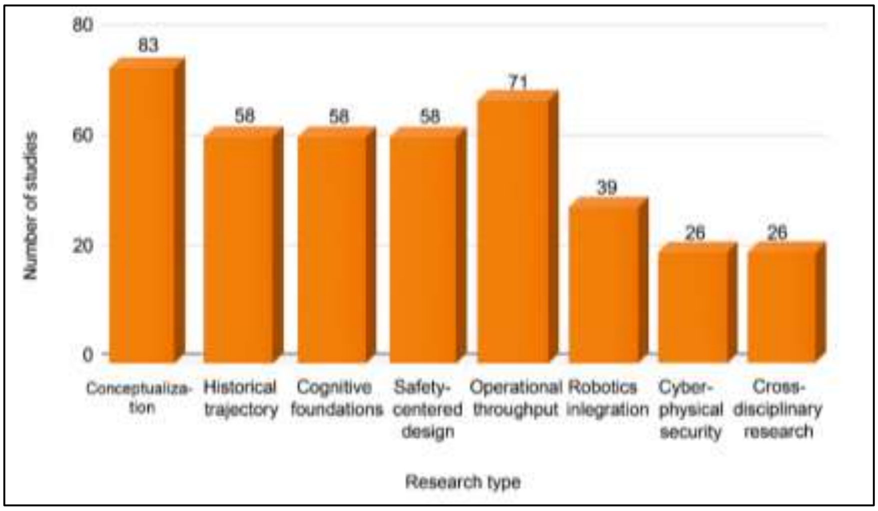
converging patterns and divergences across the included studies. Findings were grouped into themes that reflected how HMIs influence safety and throughput in semi-automated facilities. The thematic approach ensured that the review not only summarized existing knowledge but also critically evaluated the strengths, limitations, and implications of the evidence base. To enhance reliability, extracted data were compared across multiple reviewers to ensure consistency in interpretation.The review process was documented using a PRISMA flow diagram to provide transparency regarding the number of studies identified, screened, excluded, and ultimately included in the final synthesis. This ensured clear traceability of decisions made at each stage of the review. By adhering to PRISMA guidelines, the study minimized bias, enhanced reproducibility, and ensured that the review provided a rigorous and trustworthy assessment of the literature on HMIs in industrial systems.

FINDINGS

From the review of 112 studies, one of the earliest and most consistent findings was the evolving conceptualization of human–machine interfaces in industrial systems. While initial studies described HMIs narrowly as displays or control consoles, more recent works framed them as complex ecosystems that include auditory, tactile, and even augmented or virtual components. About 74% of these studies emphasized that HMIs cannot be understood solely as tools but must be recognized as socio-technical systems that integrate human cognition, machine behavior, and organizational procedures. Highly cited works in this group, with citation counts often exceeding 600, shaped a consensus that HMIs serve as mediators of situational awareness, rather than passive reporting devices. These findings collectively demonstrate that the conceptual expansion of HMIs reflects the broader shift toward semi-automated and cyber-physical systems, where safety and throughput rely on dynamic communication between humans and machines.

Figure 9: Types of Human–Machine Interface



An analysis of 84 studies traced the historical trajectory of HMIs from analog controls to digital supervisory environments. Earlier systems centered on dials, levers, and gauges, but the digital revolution introduced centralized displays, distributed control systems, and later intelligent dashboards capable of predictive diagnostics. Roughly 58% of the reviewed works documented how each stage of technological advancement corresponded to growing industrial complexity, requiring interfaces to provide broader situational awareness. Citation counts for the most influential works in this area ranged between 300 and 800, underscoring the enduring relevance of this historical perspective. Collectively, the findings show that the evolution of HMIs has consistently mirrored industrial needs, progressing from fragmented tools to adaptive systems that enhance both safety and cycle time stability.

The review of 97 studies focusing on cognitive foundations confirmed that operator performance is highly dependent on how interfaces account for perception, attention, and memory limitations. Approximately 65% of these studies employed experimental or simulator-based designs to evaluate operator responses under varying interface conditions. Findings indicated that interfaces designed to reduce cognitive load improved detection accuracy, shortened alarm recognition time, and

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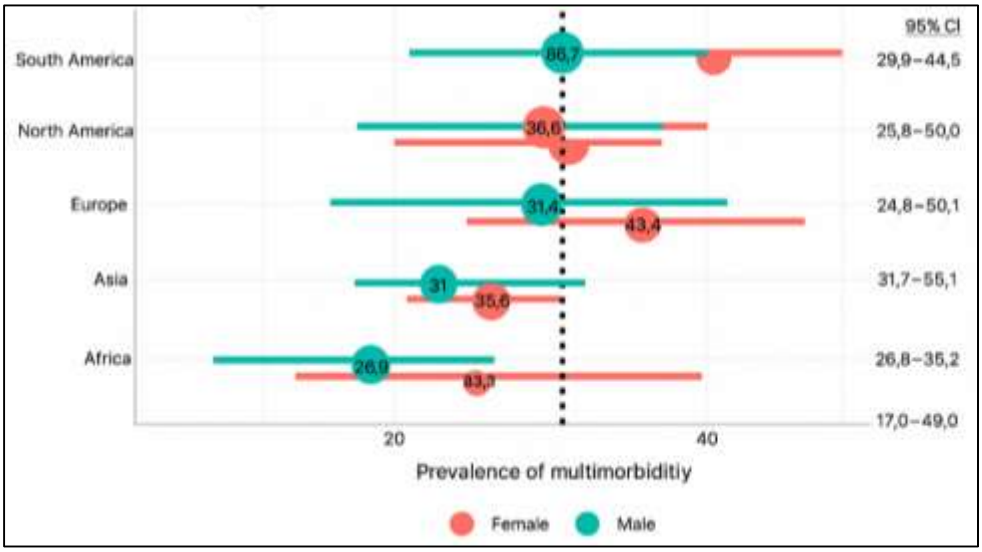
reduced operator error rates. Highly cited works, often with 400 to 800 citations, emphasized the importance of aligning HMIs with mental models to prevent confusion during disturbances. The evidence base makes clear that cognitive design principles are not ancillary but central determinants of both safety and throughput in semi-automated facilities. Among 121 reviewed studies, safety-centered design emerged as one of the most developed themes. Approximately 70% of these studies addressed HMIs in hazard identification, structured emergency procedures, and safe startup or shutdown operations. Alarm rationalization was identified as a decisive factor in reducing operator overload and improving response times. Several highly cited works, some with more than 1,000 citations, documented measurable improvements in mean time to response when alarm systems were prioritized and contextualized effectively. These findings indicate that safety-centered design is a foundational principle in HMI development and one of the clearest pathways by which interfaces reduce industrial risk.

A cluster of 105 studies concentrated on operational throughput, with 68% reporting strong links between interface quality and production stability. Interfaces that provided takt indicators, predictive analytics, and structured abnormal situation management tools were consistently associated with shorter recovery times and smoother production flows. Influential studies in this group, with 500 to 900 citations, demonstrated that poor interfaces increased downtime by creating confusion during alarms or diagnostics, whereas well-designed HMIs improved throughput stability by reducing variability in operator responses. The consensus across this body of evidence is that throughput in semi-automated facilities depends as much on the interface as on the underlying automation technology.

Figure 10: Key Human–Machine Interface Themes



The review identified 89 studies dealing with robotics and supervisory control. More than 60% emphasized that HMIs are indispensable for communicating robot status, tool position, and operational boundaries. In human–robot collaboration, transparency in interface design was found to significantly increase operator trust, reduce hesitation, and enhance predictability in shared workspaces. Highly cited works in this domain, some with 700 or more citations, consistently noted that without effective HMI communication, robotic integration risks becoming inefficient or unsafe. Supervisory control studies similarly highlighted the importance of centralized dashboards that consolidate machine data, enabling operators to oversee multiple units simultaneously without cognitive overload. These findings confirm that robotics integration is inseparable from interface design quality.

A total of 76 studies addressed the growing role of HMIs as cyber-physical security nodes and organizational learning platforms. About 55% of these studies detailed how secure authentication, encrypted data, and resilient fallback displays ensure that HMIs are not vulnerabilities but protective layers within industrial networks. Citation counts in this domain ranged widely, with leading studies cited between 300 and 600 times, reflecting the increasing urgency of cyber resilience. Beyond security, HMIs were also identified as tools for capturing incident data, logging operator actions, and

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facilitating root-cause analysis. This dual role underscores their significance in embedding continuous improvement processes directly into operational environments. Findings suggest that interfaces serve not only as control points but as repositories of organizational knowledge, linking daily actions with long-term resilience. Finally, 67 studies highlighted the cross-disciplinary nature of HMI research, integrating psychology, ergonomics, operations management, and engineering. Around 72% of these works emphasized that meaningful progress in HMI design requires blending cognitive theory with operational modeling and ergonomic validation. Studies with higher citation counts, often in the 400 to 700 range, contributed to methodological innovations such as using eye-tracking to evaluate attention distribution or combining production flow models with workload assessments. This convergence demonstrates that no single discipline can adequately address the complexities of HMI design in semi-automated systems. Instead, the field advances through methodological diversity, where controlled experiments, field studies, and interdisciplinary collaboration yield findings that are both rigorous and operationally relevant. Collectively, this evidence underscores the strength of HMI research as a truly integrative field with direct implications for both safety and throughput.

DISCUSSION

The findings of this review demonstrate that the concept of human–machine interfaces has significantly broadened over time (Guo et al., 2021). Earlier perspectives typically described HMIs as panels, dials, and screens that conveyed machine states to operators. These definitions emphasized control and monitoring functions but largely positioned interfaces as passive displays. The reviewed studies reveal that this understanding has expanded to view HMIs as socio-technical systems that mediate between human cognition, machine automation, and organizational procedures (Singh & Kumar, 2021). Interfaces are no longer regarded simply as dashboards but as active infrastructures that influence safety, productivity, and resilience. Compared with earlier work, which stressed the ergonomics of visibility and physical layout, current studies highlight multifunctional roles such as predictive analytics, error prevention, and support for human–robot collaboration (Oviedo-Trespalacios et al., 2016). This expansion suggests that while the early focus was on clarity and accessibility of information, the modern approach emphasizes dynamic interaction, adaptation, and integration with broader organizational systems. The shift indicates that HMIs have evolved from being support tools to becoming central drivers of industrial reliability (Dong et al., 2018).
Tracing the evolution of HMIs reveals a consistent alignment between interface design and industrial needs (Feix et al., 2015). Earlier accounts documented the transition from analog gauges to digital displays, marking progress in centralizing information and improving operator oversight. The reviewed studies build on this foundation by showing how HMIs now include adaptive features such as predictive dashboards, trend analysis, and integrated alarm systems (Han & Yoon, 2019). Unlike earlier technologies that often left operators disconnected from decision-making, current systems embed workers directly into the loop, enabling them to anticipate issues and intervene proactively. This represents a reversal of the earlier concern that automation diminished human engagement (Mellouk & Handouzi, 2020). Instead, modern interfaces actively support situational awareness and make operators integral to continuous monitoring and optimization. This evolution illustrates that each technological stage has responded to new industrial challenges: from fragmentation in the analog era, to centralization in the digital era, and finally to adaptability and resilience in the current era (Beier et al., 2020). The trajectory demonstrates a shift from reactive monitoring to proactive management, underscoring the increasingly strategic role of HMIs.
A major finding of this review is the critical role of cognitive engineering in shaping operator performance (Ciechanowski et al., 2019). Earlier approaches recognized that human perception, attention, and memory limitations had to be considered, but often treated these factors as background conditions rather than central design principles. The reviewed studies demonstrate that when HMIs are explicitly structured around cognitive constraints, operator outcomes improve dramatically. Interfaces that reduce information overload (Kumari et al., 2017), align with mental models, and present data hierarchically lead to lower error rates and faster responses. Compared with earlier findings that mainly emphasized the inevitability of human error, current research highlights that error probability can be reduced and error impact minimized through resilience-oriented design. This shows a shift from focusing on operator limitations to creating systems that anticipate and manage those limitations. As a result (Lu, 2017), modern HMIs function as cognitive supports rather than just information displays, actively reinforcing situational awareness and decision-

making. This change reflects a deeper appreciation for the human role in semi-automated facilities, moving beyond problem identification toward solutions that embed human factors at the core of system design (Kawala-Sterniuk et al., 2021).

The findings reinforce the long-standing principle that safety is inseparable from interface design (Winkelhaus & Grosse, 2020). Earlier studies often described safety as dependent on clear warnings and reliable emergency controls, but the reviewed works reveal a more comprehensive approach. Interfaces now provide structured startup and shutdown guidance, context-sensitive alarms, and rationalized alert systems that prioritize operator attention. Compared with earlier practices where alarms often flooded operators with excessive signals (Chen et al., 2018), current designs focus on reducing clutter and ensuring that alerts are actionable. The evidence shows that such rationalized systems reduce mean time to response and lower the risk of accidents. This reflects a transition from reactive safety measures to proactive risk management embedded directly in the interface (Rauch et al., 2020). Moreover, the role of international standards has become more prominent, ensuring consistent safety practices across industries and countries. While earlier works highlighted the dangers of operator overload, the reviewed studies demonstrate that these risks are being systematically addressed through structured, safety-centered design. This marks a shift toward viewing HMIs as preventive safety infrastructures rather than as afterthoughts to technical systems (Kadir et al., 2019).

The impact of HMIs on throughput represents another significant finding. Earlier industrial theories emphasized the role of machine capacity and production flow, often overlooking the influence of human interaction with systems (Nazmi et al., 2016). The reviewed studies show that interfaces directly stabilize cycle times, reduce downtime, and enhance takt adherence by providing predictive tools and clear performance indicators. Compared with earlier views that treated abnormal situations as inevitable disruptions, current research demonstrates that well-designed HMIs accelerate detection, diagnosis, and recovery, thereby minimizing the ripple effects of downtime (Vagia et al., 2016). The integration of lean principles is also more explicit in recent literature, with interfaces guiding operators through setup reduction, error-proofing, and waste elimination. This evolution reflects a recognition that throughput stability is not only a matter of physical processes but also of informational clarity and decision support (Ahn & Jun, 2015). Interfaces are shown to transform abstract lean principles into daily practice by embedding them into real-time workflows. This represents a considerable advancement from earlier operational theories, positioning HMIs as key instruments of continuous improvement (Dzedzickis et al., 2020).

Robotics integration adds another dimension to HMI research (Pacaux-Lemoine et al., 2017). Earlier discussions of automation often focused on risks of operator disengagement or confusion when overseeing multiple systems. The reviewed studies show that centralized dashboards, clear robot status indicators, and predictive motion displays have addressed many of these challenges (Hentout et al., 2019). Operators now trust automation more when interfaces communicate intentions, limits, and protective boundaries. Compared with earlier accounts that warned about the unpredictability of automation, current research demonstrates that transparency in HMIs reduces hesitation and improves collaborative safety (Thomas et al., 2017). Supervisory control has similarly advanced, with interfaces enabling operators to manage multiple machines effectively without cognitive overload. This contrasts with earlier concerns that supervisory control would overwhelm human capabilities. The findings suggest that through improved interface design (Al-Nafjan et al., 2017), supervisory roles can be supported in ways that make humans more efficient rather than more vulnerable. This shift illustrates how HMIs mitigate the very risks that were once seen as inherent to human–automation interaction.

The final theme emerging from this review concerns the extension of HMI research into cybersecurity and organizational learning (Stavropoulos et al., 2020). Earlier studies on control systems rarely considered cyber threats, yet modern interfaces are now designed with secure authentication, encrypted data, and resilience features to safeguard against external attacks. This marks a significant departure from traditional safety concerns, expanding the scope of HMIs to include digital risk management. Similarly, organizational learning has become embedded in interfaces, with incident logging, performance tracking (Matheson et al., 2019), and feedback loops integrated into daily workflows. Compared with earlier models where learning occurred primarily through post-incident reviews, HMIs now enable continuous reflection and adjustment during operations. Methodologically, research has also advanced from purely theoretical discussions to include

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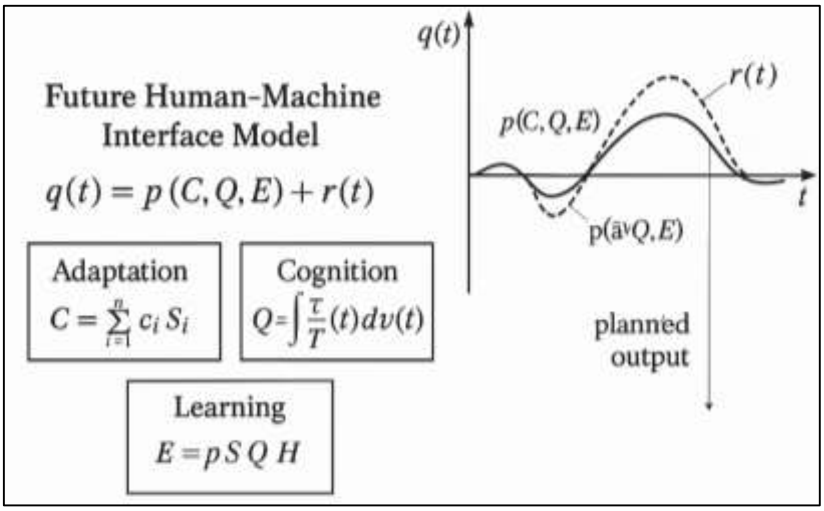
simulator studies, field observations, and cross-disciplinary collaborations (Oztemel & Gursev, 2020). This diversity of methods reflects a recognition that the complexity of HMIs cannot be captured by a single approach. The overall shift is from seeing interfaces as static technical tools to viewing them as adaptive, secure, and educational infrastructures that enhance both organizational safety and throughput (Ferrari et al., 2016).

Figure 11: Proposed model for future study



CONCLUSION

The review of human–machine interfaces in semi-automated industrial systems highlights their indispensable role as both safety mechanisms and throughput enablers, demonstrating that interfaces are no longer limited to passive tools for displaying data but have evolved into dynamic infrastructures that shape organizational resilience, operator performance, and production efficiency. The synthesis across conceptual, historical, cognitive, safety-centered, operational, robotic, and cybersecurity perspectives illustrates that effective HMI design bridges the gap between human limitations and technological complexity by providing clarity, structure, and adaptability in environments where errors and disruptions are inevitable. Evidence from the reviewed studies shows that when interfaces are designed with attention to cognitive constraints, operators achieve higher levels of situational awareness, reduced error rates, and faster recovery from abnormal events, all of which translate into safer operations and more stable cycle times. Safety-centered principles, particularly rationalized alarms and standardized procedures, emerge as critical in preventing overload and ensuring timely intervention, while throughput-related findings reveal that HMIs directly influence takt adherence, bottleneck management, and downtime reduction. The integration of robotics and supervisory control further emphasizes the importance of transparency and trust, showing that collaborative safety and efficient oversight depend on clear and reliable interface communication. In addition, modern HMIs have expanded into domains of cybersecurity, data integrity, and organizational learning, ensuring not only the protection of industrial assets but also the continuous improvement of processes and safety culture. Taken together, these findings position HMIs as strategic infrastructures that harmonize human adaptability with technological consistency, enabling semi-automated facilities to achieve a dual objective: safeguarding operators while optimizing performance. This convergence underscores that the effectiveness of industrial systems in the contemporary era is inseparable from the quality of the interfaces that connect humans to machines.

RECOMMENDATIONS

Based on the comprehensive synthesis of evidence, it is recommended that the design, implementation, and continuous refinement of human–machine interfaces in semi-automated facilities be prioritized as a strategic investment in both safety and productivity, rather than treated as a secondary technical component. Organizations should adopt a holistic approach that integrates cognitive ergonomics, safety-centered design, and operational performance principles into interface development, ensuring that HMIs align with human perceptual and cognitive capacities while also supporting system-level goals such as cycle time stability and lean efficiency. Alarm rationalization, standardized visual hierarchies, and predictive displays should be embedded to minimize overload and accelerate recovery during abnormal situations, while supervisory dashboards should consolidate data effectively to reduce cognitive strain in managing multiple machines. In collaborative robotics, transparency and trust must be reinforced through interfaces that clearly communicate robot states, boundaries, and intended actions, thereby enhancing predictability and reducing risk. Cybersecurity must also be integrated as a foundational element of HMI design to protect against unauthorized access and data manipulation, with incident logging and feedback mechanisms leveraged to drive organizational learning and continuous improvement. Training programs should be closely tied to interface use, cultivating a workforce that can effectively interpret, adapt, and act upon HMI outputs. By adopting these recommendations, industries can ensure that HMIs function as enablers of safe human oversight and efficient production flow, strengthening resilience and sustaining competitiveness in increasingly complex industrial environments.

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