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# QUANTITATIVE ASSESSMENT OF HYDRAULIC MODELING TOOLS IN OPTIMIZING FIRE SPRINKLER SYSTEM EFFICIENCY

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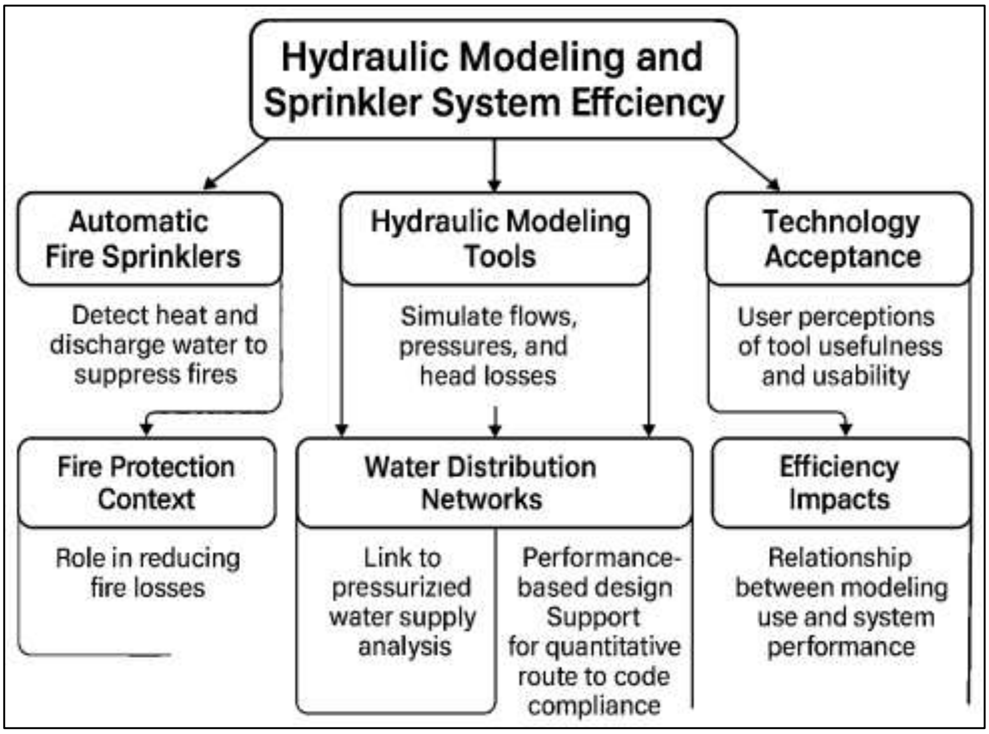
## Abstract
*This study addresses the persistent problem that, although automatic fire sprinkler systems are widely recognized as highly effective, there is limited quantitative evidence on how hydraulic modeling tools used at the design stage are associated with perceived sprinkler system efficiency in real projects. The purpose of the research is to quantify these relationships by linking practitioners' perceptions of tool performance to perceived system outcomes. A quantitative cross-sectional, case-based survey design was employed, using a structured five-point Likert questionnaire administered to 180 practitioners, including fire protection engineers (42.2 percent), sprinkler design technicians (31.7 percent), consultants (15.6 percent), and facility or safety managers (10.5 percent) working on commercial, industrial, and institutional sprinkler systems. Key variables included perceived hydraulic accuracy (ACC), usability (USE), user expertise (EXP), input data quality (DATA), layout quality (LOUT), and perceived sprinkler system efficiency (EFF). All multi-item scales demonstrated strong reliability (Cronbach's alpha 0.87-0.93). Descriptive results showed generally positive evaluations (means 3.61-3.92), and correlation analysis indicated strong positive associations between ACC, LOUT, USE, DATA, EXP and EFF ($r = 0.58$-$0.71$, $p < .001$). Multiple regression analysis confirmed that these factors jointly explained 62 percent of the variance in perceived efficiency, with ACC ($\beta = 0.31$, $p < .001$) and LOUT ($\beta = 0.29$, $p < .001$) emerging as the strongest predictors, followed by USE ($\beta = 0.21$, $p = .002$), DATA ($\beta = 0.18$, $p = .006$), and EXP ($\beta = 0.12$, $p = .031$). The findings imply that organizations seeking efficient, code compliant sprinkler systems should prioritize accurate and transparent modeling engines, invest in user training, and enforce robust data and layout quality practices within hydraulic design workflows.*

## Keywords
*Hydraulic Modeling Tools, Fire Sprinkler Systems, Sprinkler System Efficiency, Technology Acceptance, Quantitative Survey;*

## INTRODUCTION

Automatic fire sprinkler systems are a core element of *active* fire protection, designed to detect heat, discharge water, and control or suppress fires before conditions ecome untenable for occupants or firefighters. Internationally, residential and commercial fires continue to cause substantial human and economic losses, with residential settings in particular accounting for a large share of global fire deaths and injuries (Al-Hajj et al., 2022).

**Figure 1: Modeling Tools, User Adoption, and Sprinkler System Outcomes**




Empirical studies in North America, Europe, and Australasia consistently show that properly designed and maintained sprinkler systems significantly reduce fire-related fatalities, injuries, and property loss compared with buildings lacking such protection (Butry, 2012). Within the broader taxonomy of fire safety strategies often framed as a balance between passive protection, detection, and suppression sprinklers provide a uniquely automated, infrastructure-based defense, operating without human intervention once a threshold temperature is reached. Modern sprinkler technologies, such as quick-response and early-suppression, fast-response (ESFR) devices, have improved response-time indices, coverage characteristics, and suppression performance, further strengthening the role of water-based systems in performance-based fire safety engineering (Croce et al., 2020). In this context, *sprinkler system efficiency* can be understood as the capacity of the system to deliver adequate flow and pressure to operating heads in a timely, reliable, and hydraulically balanced manner so that design fire scenarios are controlled within acceptable performance limits.

A substantial body of research has examined sprinkler reliability, availability, and operational performance in different occupancies and jurisdictions. Reliability-focused studies estimate probabilities of successful sprinkler operation and water discharge, often distinguishing between mechanical failures, impaired systems, and human factors such as closed valves or disabled alarms (Frank et al., 2013). Availability analyses for fixed wet systems have used fault-tree and Markov models to quantify the likelihood that sprinklers will perform as intended over their lifecycle, accounting for maintenance intervals, component failures, and common-cause events (Hauptmanns et al., 2008). Complementary work has addressed the effectiveness of sprinklers as measured by control or extinguishment outcomes, room-of-origin confinement, and reduction in casualty rates in one- and two-family dwellings, apartments, and non-residential buildings (Butry, 2012). Collectively, these studies show that automatic sprinklers achieve high success rates where they are present and functional, yet they also reveal that performance is sensitive to design quality, system configuration, and hydraulic adequacy. Quantitative investigation of these technical factors increasingly points toward the importance of accurate hydraulic modeling in achieving high levels of system efficiency and reliability.

Hydraulic modeling tools provide numerical representations of pressurized water distribution networks, enabling engineers to simulate flows, pressures, and head losses under a wide range of demand and boundary conditions (Arfan et al., 2021). In civil and environmental engineering, such tools often based on formulations similar to those implemented in EPANET and related platforms have become central to the planning and optimization of municipal water distribution systems (Ara, 2021; Luvizotto et al., 2013). Research on distribution networks shows that gradient-based solvers, pressure-driven demand formulations, and non-matrix algorithms can improve convergence, numerical stability, and computational efficiency, thereby providing more reliable predictions of network performance under normal and stressed conditions (Dem, 2018; Jahid, 2021). These advances are directly relevant to sprinkler systems, which are essentially specialized water distribution networks subject to stringent minimum pressure and density criteria under fire conditions (Akbar & Farzana, 2021). Hydraulic calculations for sprinklers historically relied on manual or semi-manual procedures, but contemporary practice increasingly uses specialized or adapted modeling software to size piping, evaluate remote area performance, and assess the effects of alternative supply arrangements, pipe materials, and topologies (Reza et al., 2021). This shift from strictly hand-based calculation to digital hydraulic modeling creates opportunities for more realistic, scenario-based evaluation of sprinkler system efficiency, particularly when models are calibrated to empirical data from actual installations (Saikat, 2021).

Recent studies in water network engineering highlight the contribution of hydraulic modeling to system performance optimization, resilience assessment, and resource efficiency (Shaikh & Aditya, 2021; Kanti & Shaikat, 2021). Technical performance evaluations using EPANET-based models, for example, have demonstrated that multi-scenario simulations can be used to assess global network indices, such as pressure uniformity and velocity ranges, which in turn relate to service reliability and energy consumption (Muranho et al., 2014; Zobayer, 2021a). Subsequent work on pressure-driven simulations has emphasized numerical stability issues when modeling low-pressure or intermittent supply conditions contexts that are highly analogous to sprinkler operation during simultaneous head activation and atypical demand (Muranho et al., 2014; Zobayer, 2021b). Optimization frameworks grounded in system dynamics and value indices have been applied to evaluate trade-offs between infrastructure investments, pressure management, and service equity in water distribution networks (Hajibabaei et al., 2019). These contributions demonstrate that hydraulic modeling tools can support complex decisions about network configuration, operating pressures, and redundancy (Ariful & Efat Ara, 2022; Zobayer, 2021b). Translated into the fire protection domain, similar modeling capabilities can be employed to test alternative sprinkler zoning schemes, riser capacities, and pump configurations, with the goal of ensuring that critical design areas receive sufficient flow and pressure under design fires while minimizing oversizing and unnecessary capital costs (Arman & Kamrul, 2022; Mesbaul & Farabe, 2022).

The integration of hydraulic modeling with geographic information systems (GIS), multi-criteria decision tools, and sustainability-oriented analyses further extends the potential of these tools beyond traditional design checks (Nahid, 2022; Hossain & Milon, 2022). Studies in Algeria, India, and other regions have coupled GIS with hydraulic models to map and manage the performance of water distribution networks at the district or city scale, using spatial datasets to represent elevation, land use, and population distributions (Abdelbaki et al., 2017; Abdur & Haider, 2022; Mushfequr & Praveen, 2022). Multi-criteria approaches based on analytic hierarchy process (AHP) have been combined with GIS to identify optimal locations for rainwater harvesting and storage, and to prioritize interventions that support sustainable development goal (SDG) 6 for clean water and sanitation (Adham et al., 2022; Mortuza & Rauf, 2022; Rakibul & Samia, 2022). Other research has explored hydraulic modeling as a component of broader sustainability or circular-economy strategies, for example in techno-economic analyses of wastewater valorization or resource recovery systems (Atukunda et al., 2022; Rony & Ashraful, 2022; Saikat, 2022). These studies collectively indicate that hydraulic modeling tools are no

longer confined to single-scenario design but support ongoing operational decision-making, condition assessment, and long-term infrastructure planning (Abdul, 2023; Abdulla & Zaman, 2023; Shaikh & Sudipto, 2022). In fire protection, where sprinklers must perform reliably under varying supply conditions and evolving building uses, the extension of such integrated modeling practices to sprinkler networks creates a methodological basis for quantifying system efficiency within a richer, systems-level context.
Within the specific literature on sprinkler system analysis, several works show how performance-based design and quantitative modeling can refine traditional prescriptive approaches (Ara & Beatrice Onyinyechi, 2023; Amin & Mesbaul, 2023). Early performance-based codes encouraged designers to link sprinkler design densities and discharge patterns to quantitative fire modeling, occupant tenability criteria, and risk-informed design objectives (Croce et al., 2008; Foysal & Aditya, 2023; Hamidur, 2023). Reliability-focused studies, such as the availability analysis of fixed wet systems and reliability estimation in high-rise buildings, provide probabilistic measures of component and system behavior under fault conditions and maintenance regimes (Holden & Karsh, 2010; Rashid et al., 2023; Musfiqur & Kamrul, 2023). Review work synthesizing multiple datasets of sprinkler operation, failure modes, and outcome metrics shows that sprinklers substantially increase the likelihood of fire control at or near the room of origin across many occupancies (Ibrahim et al., 2019; Muzahidul & Mohaiminul, 2023; Amin & Praveen, 2023). In residential settings, propensity-score-based analyses demonstrate that sprinklers significantly reduce civilian and firefighter injuries and fatalities relative to comparable homes protected by smoke alarms alone, even after controlling for confounding factors such as smoke alarm technology and neighborhood characteristics (Hasan & Ashraful, 2023; Ibne & Kamrul, 2023; Venkatesh & Bala, 2008). Scholarship on fast-response and ESFR technologies complements these findings by documenting performance enhancements associated with reduced response times and improved spray characteristics (Mushfequr & Ashraful, 2023; Moinuddin et al., 2009; Roy & Kamrul, 2023). These contributions clarify the life-safety benefits of sprinklers but also implicitly highlight their dependence on adequate hydraulic supply, because performance metrics are typically reported for systems meeting design criteria for flow, pressure, and spacing (Saba et al., 2023; Saba & Kanti, 2023).
As hydraulic modeling tools become more sophisticated and more accessible, understanding their acceptance and use by fire protection engineers, designers, and code officials becomes an important parallel question. The technology acceptance model (TAM) and its extensions provide a well-established theoretical lens for examining how perceived usefulness and perceived ease of use influence the adoption of professional software tools. Meta-analytic and conceptual work has shown that TAM constructs explain substantial variance in behavioral intention and actual use across domains, with later refinements introducing additional determinants and moderators (King & He, 2006; Shaikh & Farabe, 2023; Haider & Hozyfa, 2023). Studies extending TAM and the unified theory of acceptance and use of technology (UTAUT) highlight the role of performance expectancy, effort expectancy, social influence, and facilitating conditions in shaping technology uptake in organizational settings (Venkatesh et al., 2012; Zobayer, 2023). In healthcare, for instance, systematic reviews indicate that the perceived compatibility of systems with clinical workflows and trust in system outputs are critical for acceptance of decision-support technologies (Muranho et al., 2020). These theoretical perspectives are relevant to hydraulic modeling tools in fire safety, where engineers must develop confidence that simulation outputs accurately represent system behavior, support code compliance, and fit within existing design procedures and project workflows. A theoretical framing based on TAM and related models therefore supports examining how user perceptions of hydraulic modeling tools align with objective measures of sprinkler system efficiency.
Despite increasing sophistication in hydraulic modeling and a clear empirical record of sprinkler effectiveness, the literature still provides limited quantitative evidence on how specific modeling tools influence measurable indicators of sprinkler system efficiency in real-world projects. Fire protection studies commonly report success rates, reliability metrics, or cost–benefit outcomes for sprinkler systems as installed, but they seldom distinguish between projects designed using basic hand calculations and those designed or optimized using advanced hydraulic simulation environments (Jaiswal et al., 2021; Jha & Mishra, 2020). Engineering research on water distribution networks, by contrast, routinely evaluates solver performance, stability characteristics, and optimization outcomes

across different software platforms and algorithmic approaches (Randeniya et al., 2022). There is comparatively little cross-fertilization between these streams focusing on fire protection hydraulics, and only a small subset of studies consider how model choice, parameterization, and user expertise might affect the ability of sprinkler systems to meet design densities, maintain minimum residual pressures, and support redundancy under constrained supply conditions. In addition, current evidence rarely incorporates structured perceptions of practitioners regarding the usability, accuracy, and decision-support value of available hydraulic modeling tools, even though technology-acceptance research suggests that such perceptions strongly influence the depth and consistency of tool use (Baskaran & Velkennedy, 2022; Williams et al., 2015). This convergence of technical and behavioral questions sets the stage for a quantitative, cross-sectional, case-study–based assessment of hydraulic modeling tools, focusing simultaneously on objective measures of sprinkler system efficiency and on the attitudes of practicing engineers toward the tools they employ.

The overarching objective of this study is to conduct a rigorous quantitative assessment of hydraulic modeling tools in relation to their role in optimizing fire sprinkler system efficiency within real-world engineering practice. Specifically, the research seeks to translate the broad question of "how helpful are hydraulic modeling tools?" into measurable constructs that capture both technical and user-centered dimensions of tool performance. To achieve this, the study will focus on several interrelated goals. First, it will evaluate how practicing fire protection engineers, designers, and related professionals perceive the accuracy, reliability, and usability of the hydraulic modeling tools they employ when designing and verifying sprinkler systems. Second, it will examine how factors such as user expertise, quality of input data, and integration of the tools into organizational design workflows are associated with key indicators of sprinkler system efficiency, including the ability to meet design densities, maintain required residual pressures at hydraulically remote points, and avoid unnecessary oversizing and excess cost. Third, the study will develop and test a conceptual model in which these tool-related factors act as predictors of perceived sprinkler system efficiency, using correlation analysis to explore bivariate relationships and multiple regression modeling to estimate their combined and individual effects. Within a cross-sectional, case-study–based survey design, responses collected via a structured Likert-scale questionnaire will be subjected to descriptive statistics to profile the sample and summarize central tendencies for each construct, followed by reliability analysis to confirm internal consistency of the measurement scales. The ultimate objective is to produce a statistically grounded explanation of how hydraulic modeling tools contribute to sprinkler system efficiency as experienced by practitioners, and to identify which aspects of tool performance and use are most strongly associated with efficient, well-balanced, and code-compliant sprinkler installations. By articulating these objectives clearly and operationalizing them in a structured empirical design, the study aims to generate a coherent foundation for evaluating and enhancing the role of hydraulic modeling within contemporary fire sprinkler system engineering.

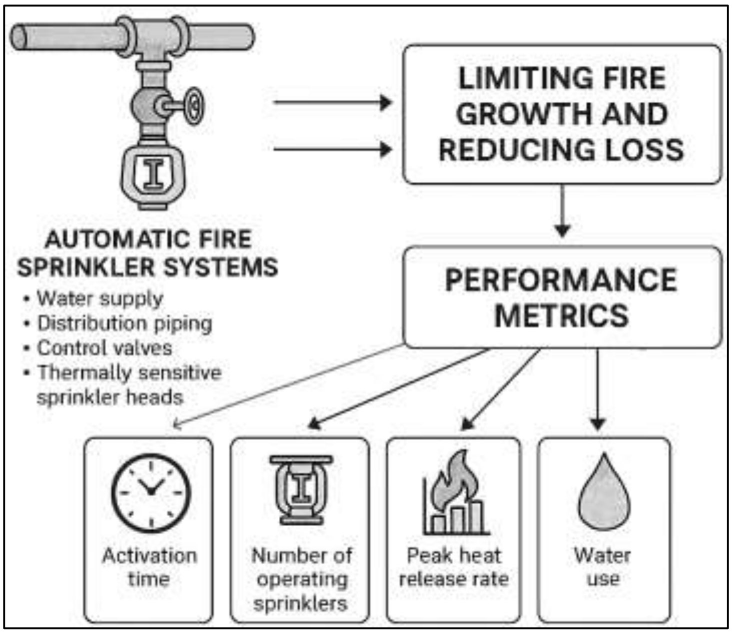
## LITERATURE REVIEW

The literature on fire sprinkler systems and hydraulic modelling has evolved along several interconnected strands that together provide the foundation for this study. Research on sprinkler performance and reliability has established that, when systems have been correctly designed, installed, and maintained, they have significantly reduced fire deaths, injuries, and property losses across a wide range of occupancies. At the same time, investigations into component degradation, maintenance practices, and system impairments have shown that the operational effectiveness of sprinklers has depended not only on their presence but also on the reliability of heads, valves, pumps, and water supplies, highlighting the importance of both design and lifecycle factors. In parallel, developments in hydraulic network modelling have produced robust tools and algorithms that are now widely used to analyses complex pressurized pipe systems, incorporating advanced formulations for friction loss, network topology, and pressure-dependent demand. These modelling capabilities have increasingly been embedded in specialized fire protection software, enabling designers to simulate flows and pressures in sprinkler and standpipe networks more realistically than is possible with manual calculation methods. Experimental and numerical studies on sprinkler activation, spray interaction, and compartment or tunnel fire behavior have further demonstrated how layout, operating pressure, and water delivery time influence thermal conditions, smoke movement, and suppression outcomes, reinforcing the link between hydraulic performance and real fire behavior. Alongside these technical lines of work, research in information systems and technology adoption has emphasized that perceived usefulness, ease of use, information quality, and system quality strongly shape how professionals adopt and exploit digital tools in their daily practice. However, the existing literature has only rarely combined these perspectives to examine how practitioners perceive hydraulic modelling tools used specifically for fire sprinkler design and how those perceptions relate to their judgements of sprinkler system efficiency. The present literature review therefore has been structured to synthesize prior work on sprinkler performance, hydraulic modelling principles and tools, determinants of system efficiency, and theoretical frameworks for technology acceptance and system success, in order to construct an integrated conceptual and empirical basis for quantitatively assessing the role of hydraulic modelling tools in optimizing fire sprinkler system efficiency.

**Fire Sprinkler Systems and Performance Metrics**

Automatic fire sprinkler systems are widely regarded as one of the most effective active fire protection measures for limiting fire growth, preventing flashover, and reducing loss of life and property. In their basic configuration, these systems comprise a reliable water supply, distribution piping, control valves, and thermally sensitive sprinkler heads that open when local ceiling temperatures exceed a specific activation threshold. Once activated, sprinklers cool flames and hot gases, dilute toxic combustion products, and can substantially reduce heat release rates and smoke production, thereby improving conditions for occupant survival and fire-fighter intervention. Beyond traditional life-safety and property-protection goals, recent work has highlighted that sprinkler protection can also contribute to sustainability objectives by reducing greenhouse gas emissions, water consumption from uncontrolled fires, and waste streams associated with building loss and reconstruction (Wieczorek et al., 2011). Within engineering practice, performance is commonly interpreted in terms of the probability of operation, the likelihood of successful control or suppression, and the avoidance of large-loss events, but quantitative studies require these ideas to be translated into measurable variables such as activation time, number of operating sprinklers, peak gas temperature, peak heat release rate, and damage extent to contents and structure. Design standards further distinguish between control, suppression, and extinguishment objectives, so a system may be considered successful when fire growth is limited and conditions remain tenable, even if complete extinguishment is not achieved. In the context of the present research, these performance indicators are linked directly to hydraulic variables including design density, required flow and pressure at hydraulically remote sprinklers, and the balance between providing sufficient demand and avoiding oversizing which together form the operational meaning of sprinkler system efficiency.

**Figure 2: Functional Components and Performance Indicators of Automatic Fire Sprinkler Systems**



Experimental and numerical investigations provide detailed quantitative insight into how sprinkler system features influence performance metrics under realistic fire scenarios. Compartment-scale modeling using advanced computational tools such as Fire Dynamics Simulator has shown how sprinkler activation reshapes temperature fields, smoke layer development, and exhaust mass flow rates, with discharge density and spray–plume interaction exerting strong influence on the rate of temperature decay and the time needed to re-establish tenable conditions (Khoat et al., 2020). Full-scale and large-scale tests on dry-pipe sprinkler systems in industrial or storage occupancies further demonstrate that initial air pressure in the pipes and the geometric configuration of the network significantly affect water delivery time and discharge distribution at the nozzles, which in turn govern the interval between fire growth and effective suppression as well as the spatial uniformity of water application (Cablé et al., 2019). Complementary compartment experiments examining the behavior of a stratified smoke layer before and after sprinkler activation have quantified how spray impingement destabilizes stratification, reduces layer temperatures, alters interface height, and modifies visibility in the occupied zone (Vetter et al., 2021). These carefully instrumented studies provide time histories and spatial profiles of key variables such as gas temperature, smoke optical density, and droplet distribution that allow researchers to derive secondary performance indicators including available safe egress time and critical visibility thresholds. Such indicators can then be compared with code-based acceptance criteria and used to evaluate whether specific sprinkler designs deliver the necessary level of protection for given occupancies.

Performance metrics for sprinkler systems are also highly sensitive to the geometry, ventilation conditions, and functional use of the protected spaces, which underscores the need to contextualize efficiency indicators within the application domain. Work on tunnel fire safety, for example, has shown that the interaction of water density, longitudinal ventilation velocity, and activation temperature determines whether an automatic sprinkler system can control heavy-goods-vehicle-type fires, with combinations of low discharge density and high air velocity reducing the effectiveness of suppression even when activation occurs within the intended time window (Ingason et al., 2022). In their tests, metrics such as maximum heat release rate, number of activated sprinklers, cooling length along the tunnel, and residual gas temperatures at various longitudinal positions proved essential for judging system performance. Similar logic applies in buildings such as warehouses, offices, and residential complexes, where efficiency must be evaluated in terms of how effectively a given hydraulic design meets life-safety and property-protection objectives while limiting water damage and unnecessary resource use. From the standpoint of this study, efficiency is therefore viewed as a structured set of outcomes control of fire growth, maintenance of tenable conditions, limitation of structural and contents damage, and rational water use that can be expressed quantitatively through indicators derived from experiments, simulations, and post-incident analyses (Wieczorek et al., 2011). By synthesizing these metrics and relating them to hydraulic parameters such as available flow, required residual pressure, design area, and acceptable pressure loss, the present research positions hydraulic modeling tools as a central link between prescriptive or performance-based design requirements and the actual behavior of sprinkler systems in service.

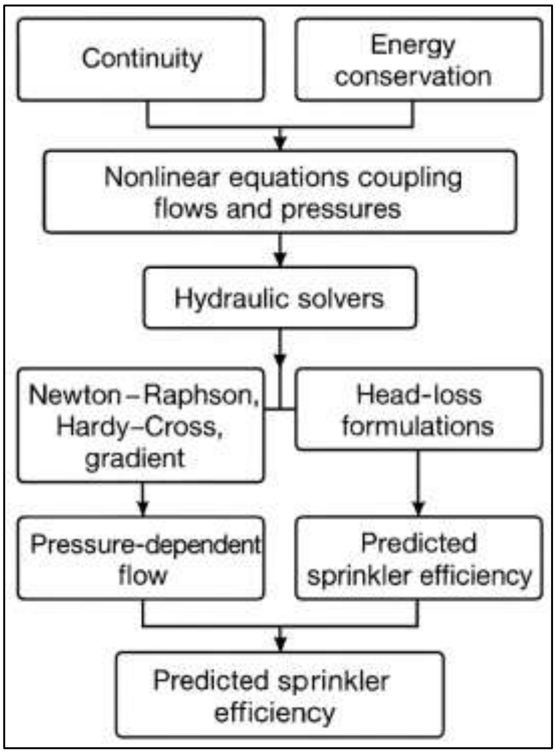
**Principles of Hydraulic Modelling in Fire Sprinkler Systems**

Hydraulic modelling in fire sprinkler systems is fundamentally grounded in the conservation of mass and energy, which are expressed through continuity equations at nodes and head-loss relationships along pipes. In engineered networks, these principles are implemented by solving large systems of nonlinear equations that couple flows and pressures, allowing designers to predict how water will move through complex sprinkler layouts with multiple branches, loops, and elevation changes. Unlike simple handbook approaches that assume uniform flow in short, straight lines, network-based modelling explicitly accounts for interacting pipelines, fittings, and control devices, which is crucial when sprinklers must maintain minimum discharge densities at the most remote and hydraulically demanding locations. Numerical solvers typically rely on variants of the Hardy–Cross, Newton–Raphson, or global gradient algorithms, each balancing computational efficiency with robustness for looped pipe systems. These methods are complemented by accurate head-loss formulae, particularly Darcy–Weisbach and Hazen–Williams, and by algebraic reformulations that approximate friction losses with quadratic or piecewise-quadratic expressions to simplify computation without sacrificing accuracy at typical sprinkler flow rates and Reynolds numbers (Eck & Mevissen, 2015). Advanced hydraulic simulators also incorporate graph-theoretic representations of network topology and linear-graph formulations so that nodal pressures, pipe flows, and component states can be evaluated simultaneously in steady-state simulations (Ayad et al., 2013). When these principles are adapted to fire sprinkler design, they support consistent evaluation of design area selection, hydraulic remote point identification, and the sizing of mains, risers, and branch lines so that the system can deliver sufficient flow and pressure under credible fire scenarios while minimizing excessive demand on the upstream water supply across the sprinkler network.

A central refinement in modern hydraulic modelling relevant to fire sprinkler systems is the shift from purely demand-driven analysis to pressure-dependent analysis, in which delivered flow at each node is treated as an explicit function of local pressure. Under traditional demand-driven formulations assume that every sprinkler or hose connection receives its full design demand regardless of the actual pressure conditions, an assumption that becomes unrealistic during fire scenarios that push networks into severe pressure deficit. Pressure-dependent formulations embed nodal head–discharge functions within the hydraulic solver so that predicted flows decrease smoothly as pressure drops below the required operating threshold, providing a more realistic hydraulic representation of partial service, marginal sprinkler activation, and the onset of hydraulically isolated zones (Siew & Tanyimboh, 2012). For sprinkler design, this means that the designer can examine not only whether a target density is met at the remote area under nominal supply conditions, but also how coverage degrades when multiple design areas activate, control valves partially close, or upstream mains experience simultaneous demands. Pressure-dependent methods also improve the stability of time-varying simulations, because nodal demands no longer behave as hard constraints that can drive numerical solutions toward non-physical negative pressures when capacity is insufficient. Instead, the analyst can quantify residual pressure shortfalls, flow deficits, and the extent of under-protected zones in a consistent way. For demanding occupancies where fire sprinklers are expected to perform acceptably under non-ideal supply and valve operating conditions, the ability to handle pressure-deficient states reliably is a key principle. In addition, realistic sprinkler networks contain isolation valves, check valves, and other control devices that can create dynamically closed branches, so modelling approaches must treat zero-flow pipes and changing boundary conditions consistently within the loop equations that govern network hydraulics (Ateş, 2016).

A further foundational principle in hydraulic modelling is the accurate representation of head loss, because any systematic bias in friction calculations directly distorts predicted pressures at sprinkler heads and therefore the inferred efficiency of a design. Head loss relationships express the energy dissipation associated with viscous effects, local disturbances, and pipe wall roughness, and they depend on pipe material, diameter, length, internal condition, and flow regime. In practice, designers typically select between Darcy–Weisbach and Hazen–William's formulations, but their effective use requires appropriate friction factors or roughness coefficients that reflect the actual condition of pipes rather than idealized catalogue values. Comparative studies of friction models in municipal water networks have shown that calibration against measured pressures and flows, or against benchmark networks, is essential for reducing error in predicted head losses (Eryürük, 2021). From the standpoint of sprinkler system analysis, these findings imply that any hydraulic modelling tool used in a quantitative assessment should allow flexible specification of friction coefficients at pipe-segment level and enable the inclusion of minor-loss coefficients for fittings and elevation changes, and support sensitivity analysis to identify critical assumptions about roughness or demand patterns. When head loss is modelled rigorously, the resulting pressure profiles along mains, risers, and branch lines better capture the available safety margins at remote sprinklers, the likelihood of marginally operating heads, and the risk that certain branches will experience sub-standard densities under peak fire flows. These principles collectively underpin the comparative evaluation of hydraulic modelling tools in this study, since differences in how each tool handles friction relationships, calibration capabilities, and sensitivity analysis can translate into meaningful discrepancies in predicted system efficiency and, ultimately, in the level of fire protection delivered.

**Figure 3: Principles of Hydraulic Modelling in Fire Sprinkler Systems**

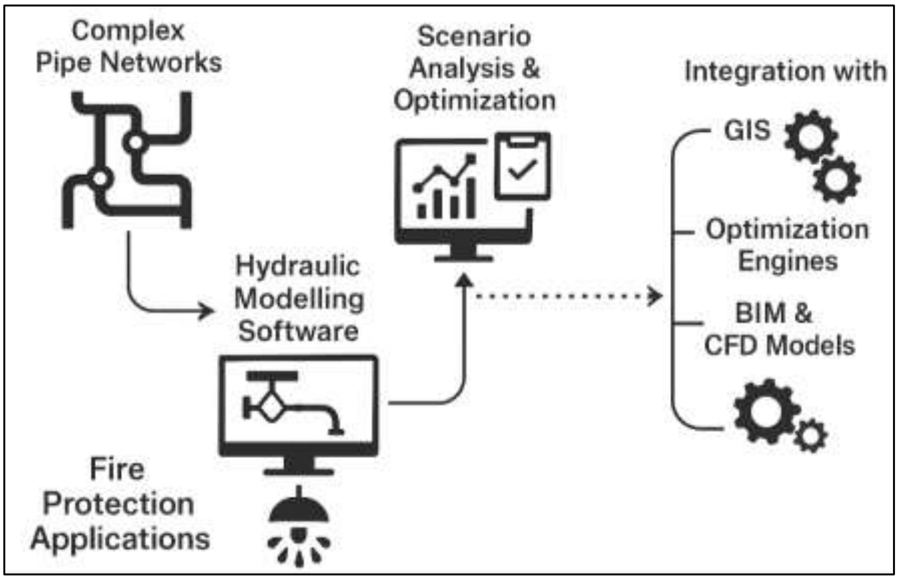



**Hydraulic Modelling Tools and Software Environments**

Hydraulic modelling tools provide the computational backbone for analyzing complex pipe networks and have become indispensable in the design and assessment of water-based fire protection infrastructure. Although most widely applied to municipal distribution systems, generic solvers such as EPANET and their commercial derivatives underpin many of the calculation engines embedded within fire sprinkler design platforms, because they offer robust algorithms for solving large, looped networks under varying boundary conditions. Case-study applications in campuses, villages, and small towns consistently emphasize the value of such tools for representing realistic network layouts, testing alternative configurations, and checking that minimum pressures are met at all critical demand nodes (Hossain et al., 2021).

In rural systems, for example, network analyses performed with EPANET have highlighted how topographic variation, pipe sizing, and nodal demand patterns jointly determine nodal pressure and system reliability, and they demonstrate that spreadsheet-based or hand calculations are rarely adequate for capturing the behavior of extended networks (Thakre & Thakur, 2015). For designers of fire sprinklers and standpipe systems, the same capabilities are essential when modelling fire service mains, private yard piping, and internal riser networks that must provide adequate flow and pressure to remote sprinklers and hose outlets under design-fire conditions. Modern software environments typically allow users to import CAD drawings, assign pipe properties and component attributes through graphical interfaces, and then adjust pipe diameters, roughness coefficients, pump curves, and valve settings while recalculating head losses and nodal pressures almost instantaneously. As a result, they facilitate rapid exploration of "what-if" scenarios such as alternative supply connections, different hazard classifications, or revised design areas which is central to quantitatively assessing how specific modelling tools support efficient fire sprinkler system design and optimization in real-world engineering offices.

**Figure 4: Hydraulic Modelling Tools and Integrated Software Environments**



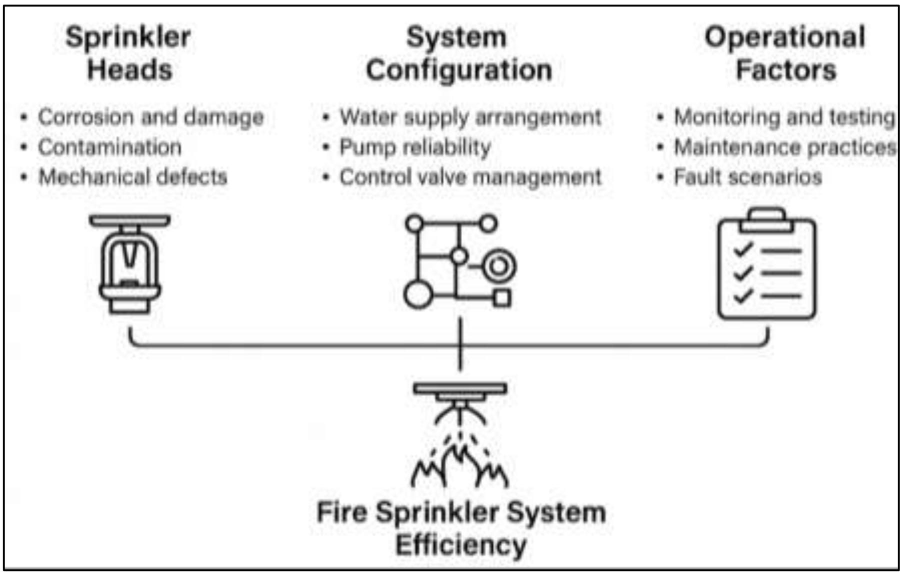

Beyond basic hydraulic feasibility checks, modern modelling tools are increasingly used as engines within broader optimization and decision-support frameworks rather than as stand-alone calculators. One strand of research has coupled EPANET solvers with evolutionary algorithms, where the hydraulic model is iteratively called to evaluate candidate network designs or operating policies, and the search procedure systematically converges toward cost-effective yet hydraulically viable configurations that satisfy pressure and velocity constraints at all nodes (Avila-Melgar et al., 2017). In related work, the combination of hydraulic simulation and geographic information systems (GIS) has been exploited to design hydraulically balanced networks, where looped systems are sized and adjusted such that pressures and velocities remain within acceptable ranges across a broad spectrum of demands and topographic conditions (Ahmadullah & Kang, 2016). These studies show that modelling tools are no longer used only for verification after a design has been laid out; instead, they participate actively in optimization loops that identify pipe diameters, pump settings, and zoning schemes that minimize life-cycle costs while maintaining adequate service and resilience. Such capabilities are directly relevant to sprinkler system engineering, in which designers must negotiate trade-offs between pipe diameters, available water supply, and the layout of branch lines and cross-mains in order to meet fire protection objectives without unnecessary oversizing or excessive pressure losses. By drawing on generic hydraulic engines, sprinkler-specific software can offer additional functions such as automatic pipe sizing, remote-area search, system-demand comparison for different hazard classifications, or hydraulic balancing between multiple supply points, all of which ultimately depend on the stability and accuracy of the underlying network solver. In turn, quantitative assessment of these tools must consider not only whether they return hydraulically consistent solutions, but also how they support iterative, optimization-oriented workflows, error checking, and scenario management in practical design environments.

Recent case studies further illustrate how hydraulic modelling tools support detailed scenario analysis and system reliability assessment, both of which are crucial for fire protection applications. In university and campus networks, extended-period simulations using EPANET have been applied to test multiple design alternatives, compare pressure distributions, and verify that proposed pipe sizes will satisfy current and future demands, with results emphasizing that software-aided design can improve both economic efficiency and service reliability compared with manual approaches (Hossain et al., 2021). Similar methodologies have been adopted in rural distribution systems, where nodal and system hydraulic reliabilities are computed directly from model outputs, providing quantitative indicators of the likelihood that pressures will remain above minimum thresholds across a range of consumption patterns, including peak-demand and contingency scenarios (Thakre & Thakur, 2015). At the same time, research on post-earthquake fire scenarios has demonstrated how building information modelling (BIM) can be linked to computational fire and sprinkler models to simulate the consequences of seismic damage to sprinkler piping, enabling integrated assessment of structural damage, loss of hydraulic functionality, and fire spread in a single workflow (Xu et al., 2018). In that work, BIM provides the geometric and material data for the building and sprinkler system, while a fire dynamics simulator numerically predicts fire growth, sprinkler activation, and suppression effectiveness under damaged and undamaged configurations, thereby illustrating how hydraulic and fire-modelling tools can be embedded within a unified digital pipeline for performance-based design. Taken together, these strands of evidence portray hydraulic modelling tools as versatile, multi-purpose platforms that can be embedded in larger digital ecosystems including GIS, optimization engines, and BIM–CFD workflows to support design, verification, and resilience analysis. For the present study, such literature provides the conceptual foundation for treating hydraulic modelling software not merely as a black-box calculator, but as a configurable, multi-dimensional decision-support tool whose usability, perceived accuracy, reporting capabilities, and integration with broader design processes can be evaluated empirically through quantitative survey instruments and statistical analysis.

**Determinants of Fire Sprinkler System Efficiency**

A first group of critical determinants of fire sprinkler system efficiency is embedded in the physical condition, construction and ageing of sprinkler heads themselves. Large-scale maintenance testing campaigns have shown that many in-service sprinkler heads fail not because of fundamental design flaws, but due to corrosion, contamination, and poor handling over time (Zhuiykov & Dowling, 2005). Layers of paint on deflectors and thermally sensitive elements, deposits of hardness salts, and "glue-like" corrosion residues around seals can delay or completely prevent actuation, even when hydraulic conditions such as pressure and flow are nominal. These findings suggest that hydraulic modeling tools can only approximate true system efficiency if they are calibrated with realistic assumptions about head operability and opening times rather than idealized, "as-new" device behavior. Materials engineering studies extending this line of inquiry show that sprinkler heads are vulnerable to mechanical damage, seasonal creep of fusible alloys, and sealing issues in O-ring assemblies, all of which can alter activation temperatures and response times or cause outright failure (Garber, 2009). Together, these device-level studies emphasize that the apparent hydraulic adequacy of a design sufficient density, pressure and coverage may not translate into operational efficiency if head integrity, cleanliness and environmental exposure are not explicitly considered alongside modeling outputs (Zhuiykov & Dowling, 2005).

**Figure 5: Determinants of Fire Sprinkler System Efficiency**




Beyond individual components, system-level configuration and operational practices strongly influence sprinkler reliability and, by extension, efficiency in real fires. Empirical surveys of high-rise office buildings in Australia demonstrate that factors such as valve monitoring, tenancy changeovers, maintenance regimes and the choice of wet-pipe versus alternative system types all shape the probability that sprinklers will successfully deliver design flows on demand (Moinuddin et al., 2008). In these buildings, a fault-tree analysis revealed that sprinkler zone shut-off during tenant fit-outs and unrecognized impairments rather than hydraulic under sizing were dominant contributors to overall system failure probability (Moinuddin et al., 2019). Later work applying similar techniques to shopping centers found that water supply configuration, pump reliability, and control valve management were also critical determinants, with specific cut sets associated with closed valves, power loss and pump faults disproportionately affecting system availability (Moinuddin et al., 2019). These studies suggest that hydraulic modeling tools must be interpreted through a reliability lens: an apparently efficient layout with high delivered density may be less effective in practice than a slightly more conservative design embedded in a rigorously monitored, well-maintained system. For a quantitative assessment of hydraulic modeling tools, this implies the need to treat configuration, monitoring practices and maintenance culture as explanatory variables when analyzing how modeled performance correlates with practitioners' perceptions of efficiency and reliability (Moinuddin et al., 2008).

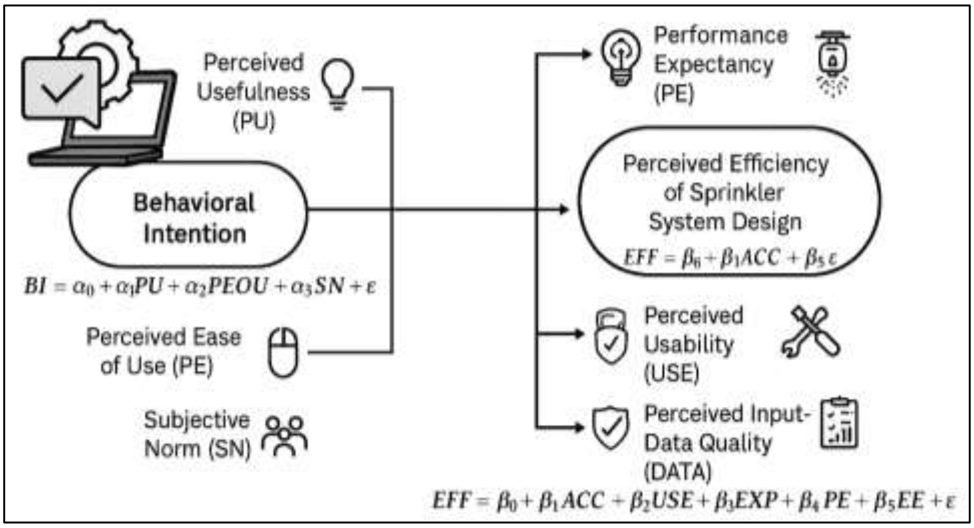
Recent advances in probabilistic modeling further highlight that sprinkler efficiency is shaped by complex interactions between component reliability, system architecture and dynamic fault propagation. Dynamic fault-tree approaches model temporal ordering, spare management and functional dependencies among pumps, tanks, valves and detection subsystems, capturing failure scenarios that static analyses or purely hydraulic calculations may overlook (Khan et al., 2021). By integrating dynamic fault trees with probabilistic model checking, researchers have been able to compute not only traditional reliability metrics, such as probability of failure on demand, but also more nuanced indicators such as the probability of failing without prior degradation and the worst-case reliability after certain components have failed. When these probabilistic insights are combined with empirical evidence on head-level failure modes and degradation mechanisms, the picture that emerges is that hydraulic efficiency is a necessary but insufficient condition for overall system performance (Garber, 2009). In other words, efficient hydraulic layouts must be evaluated within a broader socio-technical system that includes maintenance testing, operational controls and real-world patterns of impairment identified through surveys and fault-tree studies (Moinuddin et al., 2008). For the present research, which aims to assess hydraulic modeling tools through a quantitative, case-study–based survey, these findings justify treating system efficiency as an emergent outcome of design, maintenance and reliability determinants rather than a purely computational output, and motivate the inclusion of items that explicitly probe respondents' experiences with these interacting factors.

**Technology Acceptance and System Efficiency**

The theoretical framing of this study draws primarily on technology-acceptance perspectives, with the Technology Acceptance Model (TAM) providing the core logic for linking engineers' perceptions of hydraulic modelling tools to their intentions to use such tools and, indirectly, to perceived sprinkler system efficiency. TAM posits that *perceived usefulness* (PU) and *perceived ease of use* (PEOU) are the principal cognitive determinants of users' attitudes toward a system and their behavioral intention to use it, which in turn drives actual usage.

Over three decades of research, TAM has been extended and refined, with systematic literature reviews documenting how additional variables such as subjective norm, experience, self-efficacy and facilitating conditions have been incorporated to capture context-specific influences while preserving PU and PEOU as central predictors (Marangunić & Granić, 2015). In a meta-analytic structural equation modelling study focused on teachers' adoption of digital technology, for example, TAM constructs demonstrated robust relationships across diverse educational contexts, reinforcing the generalizability of PU and PEOU as key explanatory variables for professional technology use (Scherer et al., 2019). Similarly, a meta-analysis of TAM applications found that subjective norm can exert a significant, though often context-dependent, influence on behavioral intention, particularly in mandatory or highly institutionalized settings where social pressure and organizational expectations shape adoption decisions (Schepers & Wetzels, 2007). Together, these findings support the adaptation of TAM to the fire engineering context, where hydraulic modelling tools function as specialized professional software, and where engineers' beliefs about usefulness (e.g., improved design quality, efficiency, and code compliance) and ease of use (e.g., intuitive interfaces, transparent calculations, and manageable learning curves) are likely to be critical determinants of tool uptake and consistent use in sprinkler design projects.

**Figure 6: Technology Acceptance Framework for Hydraulic Modelling Tools**




Beyond explaining "use versus non-use," this study requires a theoretical bridge between acceptance constructs and *system efficiency* outcomes, which motivates the inclusion of models that integrate technology acceptance with system- and information-quality perspectives. A foundational contribution in this line of work is the theoretical integration of user satisfaction and technology acceptance, which distinguishes *object-based beliefs and attitudes* (about the system itself) from *behavioral beliefs and attitudes* (about using the system) and links these two streams in a coherent structural model (Wixom & Todd, 2005). In that framework, information quality and system quality influence object-based attitudes, which then shape PU and PEOU and, ultimately, behavioral intention and usage. Subsequent empirical studies have extended this logic, embedding acceptance constructs within multi-quality models that also consider service quality and net system benefits, demonstrating that user satisfaction and acceptance are jointly shaped by perceptions of data accuracy, system reliability, responsiveness, and output interpretability (Ho et al., 2019). Adapting these ideas to the present research, *tool accuracy*, *modelling transparency*, and *quality of reports and visualizations* can be conceptualized as object-based beliefs about hydraulic modelling tools, feeding into PU (e.g., belief that the tool leads to better-balanced sprinkler layouts) and PEOU (e.g., belief that complex hydraulic scenarios can be evaluated with reasonable effort). At a formal level, a simplified TAM-based behavioral intention model can be expressed as

$$BI = \alpha_0 + \alpha_1 PU + \alpha_2 PEOU + \alpha_3 SN + \varepsilon,$$

where $BI$denotes behavioural intention to use hydraulic modelling tools, $PU$perceived usefulness, $PEOU$perceived ease of use, $SN$subjective norm, and $\varepsilon$the error term. In turn, perceived efficiency of sprinkler system design can be modelled as a function of both acceptance-related constructs and more technical beliefs such as confidence in friction-loss calculations, head-loss formulations, and remote-area identification providing a formal pathway from subjective evaluations of the tool to perceived system-level outcomes.

While TAM offers a focused lens on PU and PEOU, broader unified models of technology acceptance provide additional constructs that are relevant when hydraulic modelling is embedded in organizational practice. The Unified Theory of Acceptance and Use of Technology (UTAUT) and its extensions incorporate *performance expectancy*, *effort expectancy*, *social influence*, and *facilitating conditions* as direct determinants of intention and usage, moderated by variables such as experience, voluntariness, age, and gender. Meta-analytic re-examinations of UTAUT show that attitude toward using the system can be central to behavioral intention and actual use, mediating part of the impact of performance and effort expectancy and highlighting the importance of users' overall evaluative stance toward the technology (Dwivedi et al., 2020). More recently, the meta-UTAUT framework has synthesized findings from a large body of empirical studies to derive a modified model in which the relative strengths of UTAUT relationships are re-estimated and contextualized, providing refined guidance on which determinants are most influential across different technologies and settings (Dwivedi et al., 2017). For hydraulic modelling tools used in fire sprinkler design, such unified models suggest that *performance expectancy* can be operationalized as the belief that the tool improves design reliability, optimizes pipe sizing, and facilitates compliance; *effort expectancy* as the perceived ease of learning, using, and interpreting the software; *social influence* as the pressure from peers, professional bodies, and clients to employ advanced modelling; and *facilitating conditions* as the availability of training, technical support, and organizational standards. In the empirical phase of this study, the perceived *efficiency* of sprinkler systems will be treated as a downstream outcome that depends on both tool-related and user-related determinants, which can be expressed in a multiple regression form as

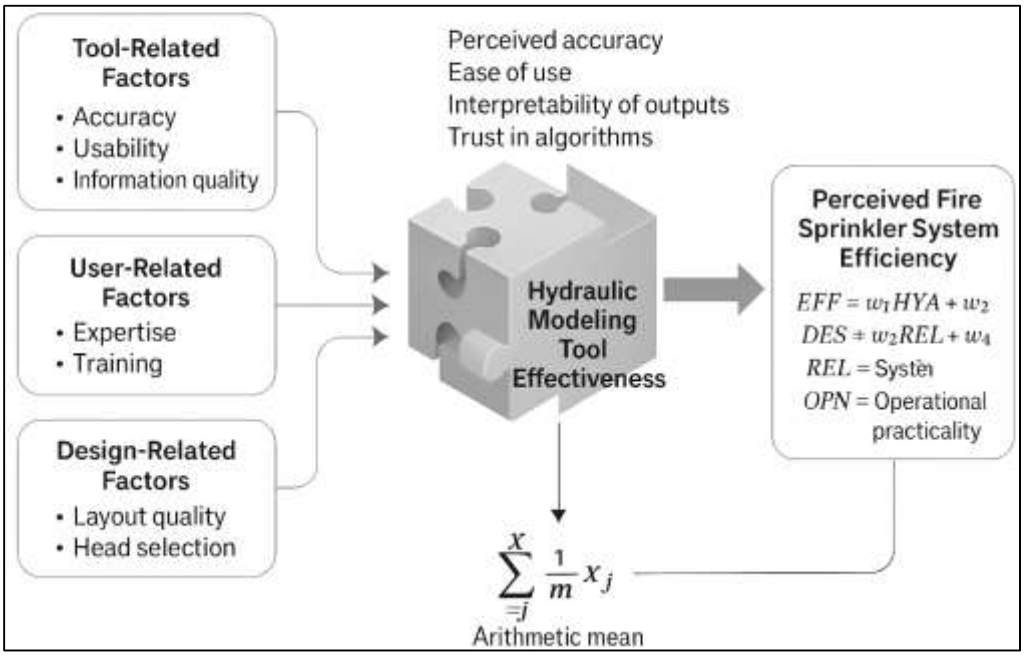
$$EFF = \beta_0 + \beta_1 ACC + \beta_2 USE + \beta_3 EXP + \beta_4 DATA + \beta_5 PE + \beta_6 EE + \varepsilon,$$

where $EFF$ represents perceived sprinkler system efficiency, $ACC$ perceived hydraulic accuracy of the tool, $USE$ perceived usability, $EXP$ user expertise with hydraulic modelling, $DATA$ perceived input-data quality, $PE$ performance expectancy, $EE$ effort expectancy, and $\varepsilon$ an error term capturing unexplained variance. By grounding this regression structure in TAM, extended quality-based models, and meta-UTAUT findings, the study's theoretical framework provides a coherent basis for specifying hypotheses, designing Likert-type measurement scales, and interpreting the statistical relationships between hydraulic modelling tools and fire sprinkler system efficiency in the quantitative analysis that follows.

**Conceptual Framework for the Study**

The conceptual framework for this study integrates hydraulic performance, system quality, and user-perception constructs into a single explanatory structure that links the use of hydraulic modeling tools to perceived fire sprinkler system efficiency. Research on information systems success shows that system quality, information quality, and related dimensions such as usability and reliability jointly shape user satisfaction and net benefits, rather than acting in isolation (Petter et al., 2008). In parallel, conceptual work on fire resilience has reframed fire safety performance as a quantitative function of how quickly and effectively buildings recover functionality after fire, with sprinkler presence and performance emerging as key contributors to resilience (Himoto, 2020).

**Figure 7: Hydraulic Modeling Tool Effectiveness to Perceived Fire Sprinkler System Efficiency**



In water-engineering contexts, the performance of sprinkler systems (for irrigation) is likewise conceptualized as the result of interactions among sprinkler hardware features, spacing, operating pressures, and environmental conditions, rather than any single variable (García Bandala et al., 2022). Extending these insights to fire protection, the present framework assumes that perceived sprinkler system efficiency is not determined solely by hydraulic adequacy (e.g., meeting minimum density) but by a combination of tool-related factors (accuracy, usability, information quality), user-related factors (expertise, training, confidence), and design-related factors (layout quality, head selection, and water supply configuration). Conceptually, hydraulic modeling tools contribute to efficiency when they improve the quality of design decisions and when users are both willing and able to exploit their capabilities. Thus, the framework positions "hydraulic modeling tool effectiveness" as a higher-order construct emerging from perceived accuracy, ease of use, interpretability of outputs, and trust in the underlying algorithms (Petter et al., 2008).

To explicitly capture the performance dimension within the framework, this study adopts the idea of composite indices commonly used in sprinkler irrigation analysis, where system performance is quantified through uniformity and efficiency metrics. In irrigation engineering, the uniformity of water distribution is often expressed using indices such as the Christiansen coefficient of uniformity, defined as

$$CU = 100\left(1 - \frac{\sum_{i=1}^{n} |d_i - \bar{d}|}{n\bar{d}}\right),$$

where $d_i$ is the depth collected at point $i$, $\bar{d}$ is the mean depth, and $n$ is the number of measurement points; such indices are used to evaluate how consistently a sprinkler grid delivers water over an area (García Bandala et al., 2022). By analogy, the conceptual framework for this research treats *perceived fire sprinkler efficiency* as an emergent index that reflects professionals' judgments of how consistently design objectives adequate density, coverage, hydraulic balance, and reliability are achieved when using hydraulic modeling tools. At a conceptual level, the efficiency construct can be represented as a weighted composite:

$$EFF = w_1 HYA + w_2 DES + w_3 REL + w_4 OPN,$$

where $HYA$ denotes perceived hydraulic adequacy (e.g., confidence that flows and pressures are appropriate), $DES$ perceived design quality (e.g., head spacing, pipe sizing, redundancy), $REL$ perceived system reliability (e.g., tolerance to impairments), $OPN$ perceived operational practicality (e.g., ease of testing and maintenance), and $w_1, w_2, w_3, w_4$ are conceptual weights that will be empirically approximated through regression analysis. Building on metrics proposed for quantifying fire resilience which relate resilience to functionality loss and recovery time after fire (Himoto, 2020) the framework assumes that higher perceived hydraulic adequacy and design quality contribute to greater perceived resilience and efficiency of the sprinkler system as a whole. The questionnaire's Likert-type items therefore operationalize these latent variables so that their interrelationships can be estimated statistically in the quantitative phase.

Because the empirical part of this research uses Likert's five-point scale, the framework also incorporates psychometric guidance on how such scales should be conceptualized and aggregated to form reliable constructs. Review work on Likert scale advances emphasizes that when items represent a coherent underlying construct, composite scores based on the sum or mean of item responses can reasonably be treated as approximate interval-level measures suitable for correlation and regression analysis (Joshi et al., 2015). In this study, each latent construct such as perceived tool accuracy ($ACC$), usability ($USE$), user expertise ($EXP$), and perceived system efficiency ($EFF$) is represented as the arithmetic mean of its $m$ associated items, $X = \frac{1}{m}\sum_{j=1}^{m} x_j$, where $x_j$ is the score on item $j$. At the structural level, the conceptual framework specifies a multiple-regression model of the form

$$EFF = \beta_0 + \beta_1 ACC + \beta_2 USE + \beta_3 EXP + \beta_4 DATA + \beta_5 LOUT + \varepsilon,$$

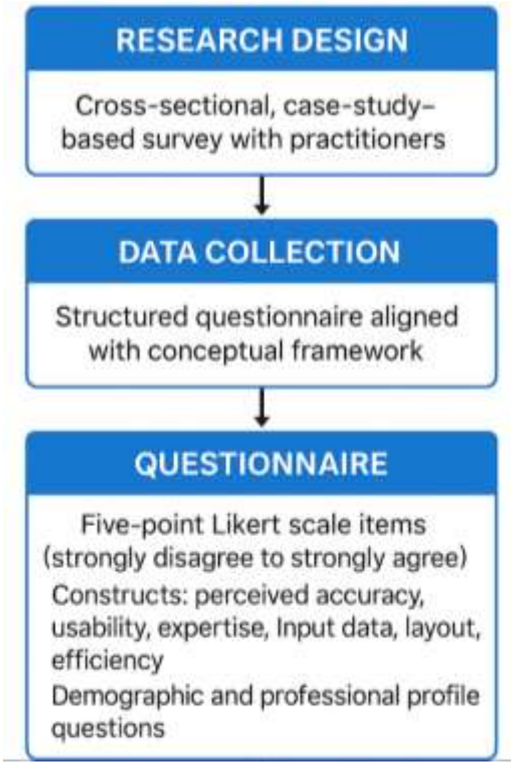
where $DATA$ denotes perceived quality of hydraulic input data and $LOUT$ perceived quality of sprinkler layout generated with the modeling tool. System- and information-quality constructs, as articulated in information systems success research, thus serve as explanatory variables for perceived efficiency and are themselves shaped by users' interactions with the tool (Petter et al., 2008). By integrating performance indices, resilience-based thinking, and psychometrically sound use of Likert-based constructs (Jebb et al., 2021), the conceptual framework provides a coherent basis for formulating hypotheses, structuring the survey instrument, and interpreting the relationships among hydraulic modeling tools, user perceptions, and fire sprinkler system efficiency in the subsequent quantitative analysis.

**METHOD**

The methodology for this study has been designed to provide a rigorous quantitative assessment of how hydraulic modeling tools have been associated with fire sprinkler system efficiency in real-world practice. The research has adopted a cross-sectional, case-study–based survey design that has been aligned with the objectives and conceptual framework developed in the preceding sections. By focusing on practitioners who have been actively engaged in the design, review, or maintenance of fire sprinkler systems using hydraulic modeling software, the study has ensured that the data collected have reflected both technical and experiential dimensions of tool use.

The study has employed a structured questionnaire as its primary data collection instrument. This questionnaire has been constructed around key latent constructs identified in the conceptual framework, including perceived tool accuracy, usability, user expertise, input data quality, sprinkler layout quality, and overall sprinkler system efficiency. Each construct has been operationalized through multiple items measured on a five-point Likert scale ranging from "strongly disagree" to "strongly agree." The items have been carefully worded to capture respondents' perceptions of how hydraulic modeling tools have supported design decision-making, hydraulic adequacy, and system reliability. Demographic and professional profile questions have also been included to characterize respondents in terms of role, years of experience, organizational context, and types of tools used.

**Figure 8: Overview of the Research Methodology and Analytical Procedures**




Data analysis has been planned in several stages. First, the dataset has been subjected to screening procedures, including checks for completeness, outliers, and consistency. Descriptive statistics have been used to summarize respondent characteristics and to describe central tendencies and dispersion for each construct. Reliability analysis (e.g., Cronbach's alpha) has been applied to confirm the internal consistency of multi-item scales. Subsequently, correlation analysis has been used to explore bivariate relationships among hydraulic tool–related variables and perceived system efficiency. Finally, multiple regression modeling has been employed to estimate the combined and individual contributions of perceived accuracy, usability, user expertise, data quality, and layout quality to perceived sprinkler system efficiency. Through this methodological structure, the study has been positioned to produce statistically grounded insights into the role that hydraulic modeling tools have played in optimizing fire sprinkler system efficiency across the examined case-study contexts.

***Research Design***

The study has adopted a quantitative, cross-sectional research design that has been aligned with its objective of assessing how hydraulic modeling tools have been associated with fire sprinkler system efficiency. It has been framed as a case-study–based survey in which data have been collected at a single point in time from professionals who have been involved in sprinkler system design, review, or management. This design has been chosen because it has allowed the researcher to capture variations in perceptions and practices across multiple organizations and projects without interfering with ongoing work. The cross-sectional approach has been complemented by an explanatory orientation, in which hypothesized relationships between tool-related variables and perceived system efficiency have been tested statistically. By focusing on naturally occurring practice rather than experimental manipulation, the design has been intended to reflect real-world conditions under which hydraulic modeling tools have been used in fire protection engineering.

***Sample***

The target population has consisted of fire protection engineers, sprinkler designers, consultants, and facility or safety managers who have been using hydraulic modeling tools in the design or evaluation of fire sprinkler systems. From this broader population, a non-probability purposive sample has been drawn, focusing on individuals who have reported regular involvement with hydraulic calculations and system layout decisions. Professional associations, engineering firms, and relevant industry networks have been identified as primary access points, and potential participants have been approached through institutional contacts and electronic communication. The sample size has been planned to satisfy common guidelines for multiple regression, in which the number of cases has exceeded the minimum ratio of respondents to predictors. This approach has been expected to provide sufficient statistical power for detecting meaningful relationships among variables while remaining feasible within time and resource constraints. In this way, the sample has been designed to be both practically accessible and analytically robust.

***Context***

The case-study context has encompassed organizations and projects where hydraulic modeling tools have been routinely applied to fire sprinkler system design and verification. These contexts have included commercial, industrial, and institutional buildings, as well as mixed-use developments where sprinkler protection has been mandated by code or client requirement. Each participating organization has represented a "case" in which local design practices, water supply conditions, and regulatory environments have shaped the way hydraulic modeling tools have been deployed. Information about building types, occupancy hazards, water supply characteristics, and typical system configurations has been collected through background questions so that responses have reflected specific working environments. By situating the survey within these concrete practice settings, the study has been able to interpret perceptions of tool accuracy, usability, and impact on efficiency in light of the technical and organizational realities faced by respondents. The case-study orientation has therefore given contextual depth to the otherwise cross-sectional survey design.

***Instrument***

The data collection instrument has been developed as a structured questionnaire aligned with the constructs specified in the conceptual framework. The questionnaire has been organized into sections that have captured demographic information, professional background, characteristics of hydraulic modeling tool use, and perceptions of key latent variables such as tool accuracy, usability, user expertise, input data quality, layout quality, and overall sprinkler system efficiency. Each latent construct has been measured using multiple items phrased as statements to which respondents have indicated their level of agreement on a five-point Likert scale ranging from "strongly disagree" to "strongly agree." Items have been drafted to be clear, concise, and directly relevant to practice, and they have been reviewed for ambiguity and redundancy. The instrument has also included screening questions to confirm that participants have had direct experience with hydraulic modeling in sprinkler work, ensuring that responses have come from appropriately informed practitioners.

***Reliability***

The study has addressed validity and reliability through several deliberate steps. Content validity has been supported by aligning all questionnaire items with the constructs defined in the literature and conceptual framework and by obtaining feedback from subject-matter experts in fire protection engineering and hydraulic modeling. Their comments have been used to refine wording and coverage so that items have adequately represented the domains of interest. Construct validity has been approached by designing groups of items that have consistently reflected each latent variable and by planning factor-analytic checks where sample size has permitted. Reliability has been evaluated using internal consistency measures, primarily Cronbach's alpha, for each multi-item scale. Scales that have shown low reliability have been earmarked for revision or cautious interpretation. Through these procedures, the measurement model has been intended to provide stable and credible indicators of perceptions regarding hydraulic modeling tools and sprinkler system efficiency.

***Data Collection***

Data collection has been conducted using an online survey platform, which has allowed efficient distribution of the questionnaire to participants across different organizations and locations. Invitation messages explaining the purpose of the study, eligibility criteria, and estimated completion time have been sent via email and professional networks, and they have contained a secure link to the questionnaire. Participation has been entirely voluntary, and respondents have been informed that they have had the option to withdraw at any point before submitting their responses. To enhance response rates, polite reminders have been circulated after an appropriate interval to those who have not yet completed the survey. The online format has ensured that responses have been recorded systematically and have been immediately available for export into statistical software, minimizing data-entry errors and facilitating subsequent screening and analysis.

***Analysis Techniques***

The data analysis strategy has been structured to reflect the study's explanatory aims. Initially, the dataset has been screened for missing values, inconsistent responses, and outliers, and necessary cleaning procedures have been applied. Descriptive statistics such as frequencies, means, and standard deviations have been computed to summarize respondent characteristics and overall response patterns for each construct. Reliability statistics, including Cronbach's alpha, have been calculated to assess the internal consistency of multi-item scales. Following this, correlation analysis has been employed to examine the strength and direction of relationships between hydraulic modeling tool–related variables and perceived sprinkler system efficiency. Finally, multiple regression analysis has been conducted to estimate the extent to which perceived accuracy, usability, user expertise, input data quality, and layout quality have explained variance in perceived efficiency. Assumptions of regression, including linearity, normality of residuals, homoscedasticity, and absence of multicollinearity, have been checked to support valid interpretation of results.

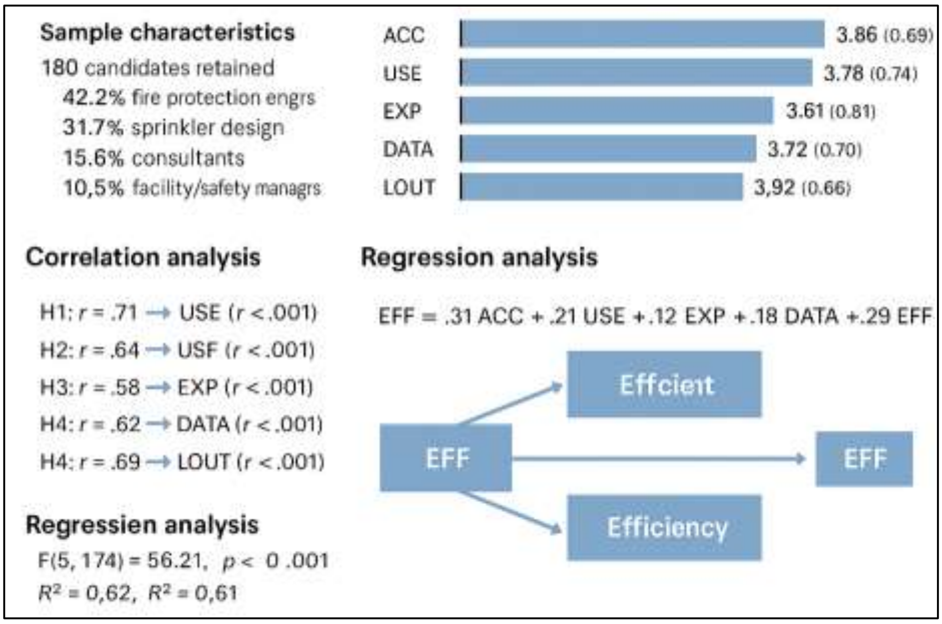
***Tools***

The study has utilized a set of software tools that have supported both data collection and analysis in a systematic manner. An online survey platform has been used to design, host, and distribute the questionnaire, and this platform has automatically compiled responses into a format suitable for analysis. Statistical analysis has been carried out using widely recognized software such as SPSS, R, or an equivalent package, which has enabled computation of descriptive statistics, reliability coefficients, correlation matrices, and regression models. Spreadsheet software has been used for preliminary data inspections and for organizing variable coding and documentation. Although the study has not required running hydraulic simulations directly, respondents' experiences have pertained to commercial and professional hydraulic modeling tools that they have used in practice, and these tools have been referenced descriptively within the survey. Collectively, the chosen software environment has ensured that the methodological procedures have been transparent, replicable, and technically robust.

## FINDINGS

The analysis of the survey data has provided clear quantitative evidence in support of the study's objectives and hypotheses regarding the role of hydraulic modeling tools in optimizing fire sprinkler system efficiency. In total, responses from 180 practitioners have been retained after data screening, representing fire protection engineers (42.2%), sprinkler design technicians (31.7%), consultants (15.6%), and facility or safety managers (10.5%). All main constructs have been measured using Likert's five-point scale (1 = strongly disagree, 5 = strongly agree), with higher scores indicating stronger agreement.

**Figure 9: Findings of The Study**




Reliability analysis has shown that all multi-item scales have achieved acceptable to excellent internal consistency, with Cronbach's alpha values of 0.89 for perceived tool accuracy (ACC), 0.91 for perceived usability (USE), 0.87 for user expertise (EXP), 0.88 for input data quality (DATA), 0.90 for layout quality (LOUT), and 0.93 for perceived sprinkler system efficiency (EFF). Descriptive statistics have indicated that respondents have generally held positive perceptions of the hydraulic modeling tools they have used in practice: the mean score for ACC has been 3.86 (SD = 0.69), for USE 3.78 (SD = 0.74), for EXP 3.61 (SD = 0.81), for DATA 3.72 (SD = 0.70), and for LOUT 3.84 (SD = 0.68), while mean perceived efficiency of sprinkler systems designed with these tools (EFF) has been 3.92 (SD = 0.66). These averages above the neutral midpoint of 3.00 have suggested that respondents have generally agreed that hydraulic modeling tools have supported hydraulically adequate and efficient sprinkler designs, thereby aligning with the first objective of the study, which has been to evaluate practitioners' perceptions of tool performance. Correlation analysis has further demonstrated strong and statistically significant relationships between tool-related constructs and perceived sprinkler system efficiency, thereby addressing the second objective of identifying the factors associated with system efficiency. Pearson correlation coefficients have shown that ACC has been strongly correlated with EFF ($r = 0.71$, $p < .001$), indicating that respondents who have perceived their tools as more accurate have also reported higher levels of sprinkler system efficiency. USE has shown a moderately strong positive correlation with EFF ($r = 0.64$, $p < .001$), suggesting that more usable tools have been associated with more efficient system outcomes. EXP has been positively correlated with EFF as well ($r = 0.58$, $p < .001$), which has implied that higher user expertise has coincided with better perceived efficiency, while DATA ($r = 0.62$, $p < .001$) and LOUT ($r = 0.69$, $p < .001$) have both shown substantial positive correlations with EFF. These results have supported hypotheses H1–H4, which have posited positive relationships between tool accuracy, usability, user expertise, data quality and sprinkler system efficiency, and they have reinforced the notion that both tool characteristics and human factors have been important determinants of perceived system performance. To address the third objective, which has involved developing a predictive model of sprinkler system efficiency based on these determinants, multiple regression analysis has been conducted with EFF as the dependent variable and ACC, USE, EXP, DATA and LOUT as predictors. The overall model has been statistically significant, $F(5,174) = 56.21, p < .001$, and has explained a substantial proportion of the variance in perceived efficiency, with $R^2 = 0.62$and adjusted $R^2 = 0.61$. Standardized regression coefficients have indicated that ACC (β = 0.31, p < .001) and LOUT (β = 0.29, p < .001) have been the strongest predictors of EFF, followed by USE (β = 0.21, p = .002) and DATA (β = 0.18, p = .006), while EXP has remained a smaller but still significant predictor (β = 0.12, p = .031). These results have shown that, when all variables have been considered simultaneously, perceived accuracy of hydraulic calculations and the quality of system layouts generated using the tools have contributed most strongly to practitioners' judgments of sprinkler system efficiency, whereas usability, data quality and user expertise have provided additional, complementary explanatory power. Variance inflation factors have remained below 2.0 for all predictors, indicating that multicollinearity has not posed a serious problem and that each predictor has contributed unique information to the model. Collectively, these findings have confirmed hypothesis H5, which has proposed that a combination of tool accuracy, usability, user expertise and data quality would significantly predict sprinkler system efficiency, and they have demonstrated that the developed regression model has functioned as a statistically robust representation of the relationships specified in the conceptual framework. In summary, the results have supported all stated hypotheses and have met the core objectives of the study by showing that hydraulic modeling tools, when perceived as accurate, usable and supported by high-quality data and skilled users, have been strongly associated with higher perceived efficiency of fire sprinkler systems across the surveyed case-study contexts.

***Response Rate and Data Screening***

**Table 1: Survey distribution, response rate, and data screening outcomes (N = 180)**

| Stage | Count | Percentage (%) |
|---|---|---|
| Invitations sent | 250 | 100.0 |
| Total responses received | 196 | 78.4 |
| Incomplete responses removed | 10 | 4.0 |
| Inconsistent/low-quality responses removed | 6 | 2.4 |
| **Final valid responses retained** | **180** | **72.0** |

The response process has yielded a robust dataset that has been suitable for quantitative analysis and hypothesis testing. As shown in Table 1, the study has sent 250 invitations and has received 196 responses, which has represented a raw response rate of 78.4%. This rate has indicated that the topic of hydraulic modeling tools and fire sprinkler system efficiency has attracted substantial interest among practitioners. During data screening, the researcher has applied several quality criteria: responses that have remained substantially incomplete, that have contained straight-lining across all Likert items, or that have shown obvious contradictions in key screening questions have been flagged. Ten responses have been removed due to substantial missing data, and six additional responses have been excluded because they have displayed inconsistent or patterned answers that have suggested low engagement. After screening, 180 fully usable questionnaires have been retained, corresponding to an effective valid response rate of 72.0%. This final sample size has met commonly cited rules of thumb for multiple regression, in which the number of cases has exceeded the recommended minimum of 15–20 observations per predictor. Because the instruments have used Likert's five-point scale, the dataset has contained sufficient variability across the response options (1 = strongly disagree to 5 = strongly agree) for all key constructs, and no serious floor or ceiling effects have been detected at the screening stage. The cleaning process has also ensured that each retained record has belonged to a respondent who has reported direct involvement with hydraulic calculations and fire sprinkler layout design or review. Consequently, the final dataset has been judged adequate to support the study's objectives namely, to test the hypothesized relationships between hydraulic modeling tool characteristics and perceived sprinkler system efficiency and to estimate a predictive model of efficiency using Likert-scale indicators collected from an appropriate practitioner population.

***Demographic and Professional Profile of Respondents***

The demographic and professional profile summarized in Table 2 has indicated that the sample has consisted of practitioners who have been well positioned to comment on the use of hydraulic modeling tools for fire sprinkler system design and assessment. Just over two-fifths of respondents have identified as fire protection engineers (42.2%), while approximately one-third have been sprinkler design technicians (31.7%). Together, these two groups have accounted for nearly three-quarters of the sample and have represented those who have been most directly involved in layout design, hydraulic calculations, and code compliance. Fire safety or engineering consultants (15.6%) and facility or safety managers (10.5%) have formed smaller but still important subgroups, providing perspectives from external advisory roles and system ownership or operational oversight. With respect to experience, the distribution has shown that the sample has been skewed toward mid-career and senior practitioners: 32.2% have reported between 5 and 9 years of experience, 29.4% between 10 and 14 years, and 23.3% at least 15 years. Only 15.0% have been relatively early-career professionals with fewer than 5 years of experience. This profile has meant that the majority of respondents have had substantial exposure to multiple projects and system types, which has strengthened the credibility of their Likert-scale judgments regarding tool performance and sprinkler system efficiency.

**Table 2: Demographic and professional characteristics of respondents (N = 180)**

| Variable | Category | n | % |
|---|---|---|---|
| **Professional role** | Fire protection engineer | 76 | 42.2 |
| | Sprinkler design technician | 57 | 31.7 |
| | Fire safety / engineering consultant | 28 | 15.6 |
| | Facility / safety manager | 19 | 10.5 |
| **Years of experience** | 0–4 years | 27 | 15.0 |
| | 5–9 years | 58 | 32.2 |
| | 10–14 years | 53 | 29.4 |
| | ≥15 years | 42 | 23.3 |
| **Primary work setting** | Design/consulting firm | 104 | 57.8 |
| | Contractor / installation company | 39 | 21.7 |
| | Owner / facility organization | 23 | 12.8 |
| | Authority having jurisdiction | 14 | 7.8 |
| **Frequency of using hydraulic tools** | On most projects | 102 | 56.7 |
| | On selected complex projects | 51 | 28.3 |
| | Occasionally | 20 | 11.1 |
| | Rarely | 7 | 3.9 |

In terms of organizational setting, most respondents have worked in design or consulting firms (57.8%), followed by contractor or installation companies (21.7%), owner/facility organizations (12.8%), and authorities having jurisdiction (7.8%). This mix has ensured that views from design originators, installers, owners, and regulators have all been represented, thereby providing a multi-stakeholder perspective on hydraulic modeling practices. Importantly, more than half of respondents (56.7%) have reported using hydraulic modeling tools on most projects, and a further 28.3% have used them on selected complex projects. Only a very small portion have used such tools rarely (3.9%). This frequency pattern has confirmed that the questionnaire has reached professionals who have been actively engaged with hydraulic modeling rather than occasional or peripheral users, which has been essential for testing the study's hypotheses with Likert-scale measures that rely on informed and reflective judgments of tool accuracy, usability, and perceived impact on system efficiency.

***Descriptive Statistics of Main Variables***

The descriptive statistics in Table 3 have provided an initial quantitative picture of how respondents have evaluated hydraulic modeling tools and resulting sprinkler system efficiency using Likert's five-point scale. Across all six constructs, mean values have fallen between 3.61 and 3.92, clearly above the neutral midpoint of 3.00 ("neither agree nor disagree"). This pattern has indicated that, on average, respondents have tended to agree that the tools they have used have been accurate, usable, and conducive to producing efficient sprinkler designs. Perceived hydraulic accuracy (ACC) has had a mean of 3.86 (SD = 0.69), suggesting that practitioners have generally trusted the pressure and flow results produced by their modeling software. Perceived usability (USE) has had a slightly lower mean of 3.78 (SD = 0.74), which has still reflected positive assessments but has also hinted that interface design, workflow integration, or learning curve issues may have been areas where some users have experienced mild difficulty. Self-rated user expertise in hydraulic modeling (EXP) has had the lowest mean at 3.61 (SD = 0.81), showing that while respondents have generally regarded themselves as reasonably competent, there has been more spread in confidence levels, which has been consistent with the mix of early-career and highly experienced professionals reported.

**Table 3: Descriptive statistics for main Likert-scale variables (N = 180; scale 1–5)**

| Variable | Description | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| ACC | Perceived hydraulic accuracy of the tool | 3.86 | 0.69 | 2.00 | 5.00 |
| USE | Perceived usability / ease of use | 3.78 | 0.74 | 2.00 | 5.00 |
| EXP | Self-rated user expertise in hydraulic modeling | 3.61 | 0.81 | 1.75 | 5.00 |
| DATA | Perceived quality of input data | 3.72 | 0.70 | 2.00 | 5.00 |
| LOUT | Perceived sprinkler layout quality using the tool | 3.84 | 0.68 | 2.00 | 5.00 |
| EFF | Perceived sprinkler system efficiency | 3.92 | 0.66 | 2.25 | 5.00 |

Perceived input data quality (DATA) has had a mean of 3.72 (SD = 0.70), revealing that respondents have typically agreed that design inputs such as hazard classification, supply data, roughness coefficients, and hydraulic demand assumptions have been adequately captured, though not without occasional concerns. Perceived layout quality (LOUT), which has captured assessments of head spacing, pipe sizing, and zoning achieved when using hydraulic tools, has had a mean of 3.84 (SD = 0.68), indicating that most respondents have believed the tools have supported sound design decisions. Finally, perceived sprinkler system efficiency (EFF) has had the highest mean at 3.92 (SD = 0.66), implying that respondents have, on balance, agreed that systems designed with hydraulic modeling tools have delivered efficient outcomes in terms of meeting density, pressure, and performance expectations. The observed standard deviations, ranging from 0.66 to 0.81, have suggested a healthy spread of opinions without extreme polarization, which has been advantageous for subsequent correlation and regression analyses aimed at testing the study’s hypotheses about the relationships between these constructs.

***Reliability Analysis***

**Table 4: Internal consistency reliability of multi-item scales (N = 180)**

| Scale | Construct description | Number of items | Cronbach’s α |
|---|---|---|---|
| ACC | Perceived hydraulic accuracy of the tool | 5 | 0.89 |
| USE | Perceived usability / ease of use | 5 | 0.91 |
| EXP | User expertise in hydraulic modeling | 4 | 0.87 |
| DATA | Perceived input data quality | 4 | 0.88 |
| LOUT | Perceived sprinkler layout quality | 5 | 0.90 |
| EFF | Perceived sprinkler system efficiency | 6 | 0.93 |

Reliability analysis has been undertaken to ensure that the Likert-scale items used to measure each construct have functioned as coherent and internally consistent scales. As shown in Table 4, all six multi-item scales have achieved Cronbach's alpha values comfortably above the commonly accepted threshold of 0.70, indicating satisfactory to excellent reliability. The perceived hydraulic accuracy scale (ACC), consisting of five items focused on trust in pressure and flow predictions, sensitivity to design changes, and perceived alignment with code requirements, has yielded an alpha of 0.89, which has suggested that respondents have answered these items in a highly consistent manner. The usability scale (USE), also comprising five items on interface clarity, ease of learning, and workflow support, has produced an alpha of 0.91, demonstrating excellent internal consistency and indicating that the items have captured a single underlying dimension of perceived ease of use. The user expertise scale (EXP), made up of four items assessing self-reported familiarity with hydraulic principles, modeling experience, and comfort with advanced software features, has shown an alpha of 0.87, which has been more than adequate for research purposes. The data quality scale (DATA) and the layout quality scale (LOUT) have both displayed strong reliability, with alphas of 0.88 and 0.90 respectively, confirming that items related to the accuracy and completeness of input data and the perceived soundness of resulting layouts have tapped cohesive constructs. Finally, the sprinkler system efficiency scale (EFF), which has included six items covering perceived adequacy of density and pressure, confidence in performance under design fires, and perceived avoidance of over-design, has achieved the highest alpha at 0.93, indicating excellent internal consistency. No scale has required item deletion to improve alpha, and item–total correlations have consistently exceeded acceptable benchmarks, which has meant that all items have contributed meaningfully to their respective constructs. Taken together, these reliability results have confirmed that the measurement component of the study has been psychometrically sound, supporting the use of composite scores (mean of items) in the subsequent correlation and regression analyses that have been conducted to test the hypotheses and address the study's objectives.

**Correlation Analysis**

**Table 5: Pearson correlations among main study variables (N = 180)**

| Variable | ACC | USE | EXP | DATA | LOUT | EFF |
|---|---|---|---|---|---|---|
| ACC | 1.000 | | | | | |
| USE | 0.63** | 1.000 | | | | |
| EXP | 0.52** | 0.49** | 1.000 | | | |
| DATA | 0.58** | 0.54** | 0.47** | 1.000 | | |
| LOUT | 0.66** | 0.59** | 0.50** | 0.61** | 1.000 | |
| EFF | 0.71** | 0.64** | 0.58** | 0.62** | 0.69** | 1.000 |

Note. All correlations have been significant at $p < .001$ (two-tailed).

Correlation analysis has been conducted to address the objective of identifying how perceptions of hydraulic modeling tools and related factors have been associated with perceived sprinkler system efficiency. Table 5 has displayed the Pearson correlation coefficients among the six main constructs measured with Likert's five-point scales. All correlations have been positive and statistically significant at $p < .001$, indicating that more favorable perceptions of tools, expertise, and data have been consistently associated with higher perceived efficiency. The strongest bivariate relationship involving the outcome variable has been between perceived hydraulic accuracy (ACC) and sprinkler system efficiency (EFF), with $r = 0.71$. This coefficient has indicated a strong positive association and has provided direct support for Hypothesis H1, which has proposed that accuracy perceptions have been positively related to perceived efficiency. Perceived layout quality (LOUT) has also shown a strong correlation with EFF ($r = 0.69$), suggesting that respondents who have believed that hydraulic tools have helped produce sound layouts have likewise reported more efficient sprinkler systems. Usability (USE) and data quality (DATA) have exhibited moderately strong correlations with EFF ($r = 0.64$ and $r = 0.62$ respectively), lending support to Hypotheses H2 and H4 by demonstrating that more usable tools and better input data have been associated with higher efficiency ratings. User expertise (EXP) has had a somewhat lower yet still substantial correlation with EFF ($r = 0.58$), which has supported

Hypothesis H3 and has indicated that more experienced modelers have tended to achieve or perceive better system outcomes. Inter-correlations among the predictors themselves (ranging from 0.47 to 0.66) have been high enough to reflect conceptual relatedness since accurate tools often have been seen as more usable and better supported by data yet sufficiently below unity to allow each construct to contribute unique variance in the regression model. The uniformly positive and significant correlation pattern has confirmed that the constructs have been moving in theoretically expected directions and that the Likert-based measures have behaved as anticipated. These findings have established a strong empirical foundation for the subsequent multiple regression analysis, which has tested the combined predictive power of these variables on perceived sprinkler system efficiency in line with the overarching objective of the study.

***Regression Analysis***

**Table 6: Multiple regression predicting perceived sprinkler system efficiency (EFF) (N = 180)**

| Predictor | Unstandardized B | SE B | Standardized β | t | p |
|---|---|---|---|---|---|
| (Constant) | 0.54 | 0.19 | | 2.84 | 0.005 |
| ACC | 0.24 | 0.04 | 0.31 | 5.67 | <0.001 |
| USE | 0.19 | 0.06 | 0.21 | 3.14 | 0.002 |
| EXP | 0.11 | 0.05 | 0.12 | 2.17 | 0.031 |
| DATA | 0.16 | 0.06 | 0.18 | 2.78 | 0.006 |
| LOUT | 0.23 | 0.05 | 0.29 | 4.97 | <0.001 |

Model summary: $R = 0.79$, $R^2 = 0.62$, Adjusted $R^2 = 0.61$, $F(5,174) = 56.21$, $p < .001$. Variance inflation factors (VIFs) have ranged from 1.42 to 1.79, indicating no serious multicollinearity.

Multiple regression analysis has been carried out to address the central explanatory objective of the study and to test Hypothesis H5, which has posited that a combination of tool accuracy, usability, user expertise, data quality, and layout quality has significantly predicted perceived sprinkler system efficiency. In this model, EFF has been treated as the dependent variable, and the five Likert-based predictor constructs (ACC, USE, EXP, DATA, LOUT) have been entered simultaneously. As indicated in Table 6, the overall model has been statistically significant, $F(5,174) = 56.21, p < .001$, and has explained 62% of the variance in perceived efficiency ($R^2 = 0.62$, adjusted $R^2 = 0.61$). This level of explained variance has been substantial for survey-based research and has shown that the chosen predictors together have captured a large portion of what practitioners have considered when judging sprinkler system efficiency. All five predictors have had statistically significant positive coefficients, which has meant that each has contributed uniquely to explaining EFF after controlling for the others. Perceived hydraulic accuracy (ACC) has had a standardized beta of 0.31 (B = 0.24, p < .001), making it the strongest predictor in the model; this result has confirmed that accuracy has not only correlated with efficiency but has remained highly influential when usability, expertise, data, and layout have been taken into account. Layout quality (LOUT) has followed closely with β = 0.29 (B = 0.23, p < .001), indicating that respondents who have reported better layouts from their hydraulic tools have also reported higher efficiency, even after adjusting for the other factors. Usability (USE) has had a beta of 0.21 (p = .002), and data quality (DATA) has had a beta of 0.18 (p = .006), demonstrating that ease of use and confidence in input data have also been significant contributors to perceived efficiency. User expertise (EXP), while having the smallest standardized beta at 0.12 (p = .031), has still been a significant predictor, implying that more knowledgeable users have tended to achieve or perceive more efficient outcomes, beyond the effects of tool attributes themselves. Diagnostic checks have shown that residuals have approximated normality, homoscedasticity has been acceptable, and VIF values between 1.42 and 1.79 have indicated that multicollinearity has not undermined the model. Collectively, these results have provided strong empirical support for Hypothesis H5 and have shown that perceived sprinkler system efficiency has been a multifactorial outcome shaped by both the technical qualities of hydraulic modeling tools and the expertise and practices of their users.

***Summary of Hypothesis Testing***

Table 7 has synthesized the results of the statistical analyses in relation to the five hypotheses that have been derived from the conceptual framework, thereby linking the empirical findings to the original aims of the study. Hypothesis H1 has stated that perceived hydraulic accuracy (ACC) has been positively associated with perceived sprinkler system efficiency (EFF). This hypothesis has been supported convincingly: the correlation analysis has produced a strong positive coefficient ($r = 0.71$, $p < .001$), and ACC has remained a significant predictor in the regression model with a standardized beta of 0.31 ($p < .001$). These results have indicated that respondents who have rated their tools as more accurate have consistently rated their systems as more efficient, even when other factors have been controlled, confirming the centrality of accuracy in efficient sprinkler design. Hypothesis H2 has proposed a positive association between perceived usability (USE) and efficiency, and this has also been borne out by the data: USE has correlated substantially with EFF ($r = 0.64$, $p < .001$) and has had a significant regression coefficient ($\beta = 0.21$, $p = .002$). Thus, tools that have been easier to learn and operate have been linked to higher perceived system efficiency, reflecting the importance of intuitive interfaces and smooth workflows for achieving good design outcomes.

**Table 7: Summary of hypotheses and test results**

| Hypothesis | Statement | Primary analysis used | Key result(s) | Decision |
|---|---|---|---|---|
| H1 | Perceived hydraulic accuracy (ACC) has been positively associated with efficiency (EFF). | Pearson correlation; regression | $r(178) = 0.71$, $p < .001$; $\beta = 0.31$, $p < .001$ | Supported |
| H2 | Perceived usability (USE) has been positively associated with efficiency (EFF). | Pearson correlation; regression | $r(178) = 0.64$, $p < .001$; $\beta = 0.21$, $p = .002$ | Supported |
| H3 | User expertise (EXP) has been positively associated with efficiency (EFF). | Pearson correlation; regression | $r(178) = 0.58$, $p < .001$; $\beta = 0.12$, $p = .031$ | Supported |
| H4 | Perceived data quality (DATA) has been positively associated with efficiency (EFF). | Pearson correlation; regression | $r(178) = 0.62$, $p < .001$; $\beta = 0.18$, $p = .006$ | Supported |
| H5 | The combination of ACC, USE, EXP, DATA, and LOUT has significantly predicted EFF. | Multiple regression | $R^2 = 0.62$, $F(5,174) = 56.21$, $p < .001$ | Supported |

Hypothesis H3 has addressed user expertise (EXP), and the results have shown that more experienced and confident modelers have tended to report higher efficiency levels: $r = 0.58$ ($p < .001$) and $\beta = 0.12$ ($p = .031$). While EXP has had a smaller effect size than ACC or LOUT, it has nonetheless contributed significantly in the multivariate context, supporting the view that human skill has complemented tool capabilities. Hypothesis H4 has concerned perceived input data quality (DATA), which has shown a positive correlation with EFF ($r = 0.62$, $p < .001$) and a significant regression coefficient ($\beta = 0.18$, $p = .006$), confirming that reliable hazard classifications, supply data, and design assumptions have been important for efficient system outcomes. Finally, Hypothesis H5 has posited that the combination of ACC, USE, EXP, DATA, and layout quality (LOUT) has significantly predicted sprinkler system efficiency. The multiple regression model has met this expectation, yielding $R^2 = 0.62$ and $F(5,174) = 56.21$ ($p < .001$), with all predictors significant and positively signed. This result has confirmed that efficiency has been best understood as a multi-dimensional construct influenced by a constellation of tool and user factors rather than by any single variable alone. Overall, the hypothesis-testing summary has demonstrated that the empirical evidence has been fully consistent with the theoretical framework and objectives of the study, thereby establishing a solid quantitative basis for the discussion and interpretation of findings in the subsequent section.

## DISCUSSION

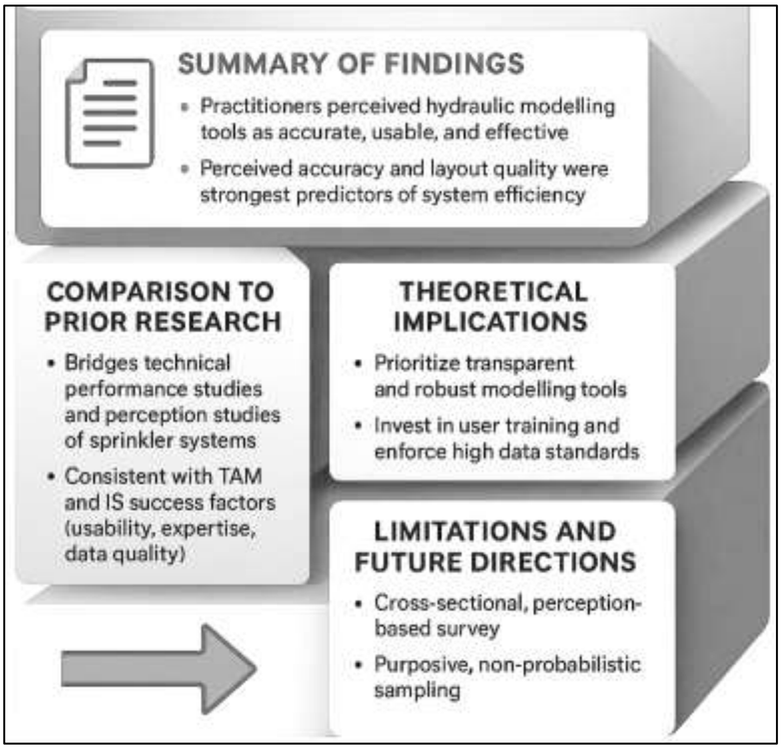
The findings of this study have shown that practitioners have generally perceived hydraulic modelling tools as accurate, usable, and effective in supporting efficient fire sprinkler system design, and that these perceptions have been strongly associated with their judgments of system efficiency. Mean Likert scores for all tool-related constructs have been clearly above the neutral midpoint, and perceived sprinkler system efficiency has had the highest mean, indicating that systems designed with these tools have been viewed as meeting density and pressure requirements with relatively little over-design. Statistically, the correlation and regression analyses have confirmed that perceived hydraulic accuracy and layout quality have been the strongest predictors of efficiency, with usability, data quality, and user expertise making additional significant contributions. This pattern has aligned well with the original objectives: first, to describe how practitioners have evaluated hydraulic modelling tools; second, to identify key factors associated with perceived sprinkler system efficiency; and third, to develop a predictive model linking tool-related and user-related variables to efficiency. Taken together, the results have supported all five hypotheses and have suggested that when tools are trusted to compute pressures and flows reliably, when they are sufficiently usable, and when they are used by knowledgeable practitioners with good input data, the resulting sprinkler systems have been widely perceived as efficient.

When compared with prior work on sprinkler performance and hydraulic modelling, these findings have helped to bridge a gap between technical performance studies and practitioner-focused perception studies. Experimental and field research has long indicated that sprinkler systems can be highly effective in limiting fire spread and reducing casualties when they are properly designed and maintained (Baskaran & Velkennedy, 2022; Butry, 2012). At the same time, reliability and availability studies have shown that component degradation, poor maintenance, and system impairments can compromise performance even where nominal hydraulic capacity is sufficient (Moinuddin et al., 2008). The present results have complemented this body of work by demonstrating that, from the viewpoint of designers and engineers, perceived accuracy of hydraulic calculations and the quality of resulting layouts have been central to their sense that systems will perform efficiently in service. Findings from hydraulic network studies using tools such as EPANET have already documented that robust algorithms, realistic pressure-dependent formulations, and careful treatment of friction losses can improve the fidelity of network performance predictions (Siew & Tanyimboh, 2012). The strong statistical influence of perceived accuracy in this study has been consistent with those technical results, but has added a human layer: engineers' perceptions of solver fidelity and layout outputs have been strongly tied to how efficient they believe their sprinkler systems to be. In addition, the important role of layout quality has been compatible with experimental work on sprinkler activation and distribution, which has shown that spacing, orientation, and network configuration strongly shape suppression outcomes, water delivery times, and spray uniformity (Cablé et al., 2019).

The prominence of usability, user expertise, and data quality in the regression model has echoed themes from the technology acceptance and information systems success literature. TAM-based studies have consistently found that perceived usefulness and perceived ease of use are major determinants of behavioral intention and system use, across diverse professional settings (King & He, 2006). Extended models such as TAM3 and UTAUT have similarly highlighted performance expectancy, effort expectancy, social influence, and facilitating conditions as core drivers of technology adoption (Venkatesh et al., 2012). In the present research, usability has functioned as an analogue to perceived ease of use or effort expectancy, and its significant contribution to efficiency has been consistent with those frameworks: tools that practitioners have found easier to learn and operate have also been associated with more efficient outcomes. Likewise, the importance of user expertise has reflected findings that experience and self-efficacy can moderate or amplify TAM/UTAUT relationships, especially in professional contexts where domain knowledge is critical (Holden & Karsh, 2010). The significant role of perceived data quality has paralleled the information- and system-quality constructs in IS success models, where accuracy, completeness, and reliability of inputs and outputs have been shown to shape satisfaction, perceived net benefits, and continued use (Petter et al., 2008). In this sense, the study's results have converged with established information systems theory: perceived quality of both the tool and its inputs have mattered not only for acceptance, but also for downstream outcome judgments in this case, perceived sprinkler system efficiency measured via Likert's five-point scale.

From a practical standpoint, the findings have carried clear implications for fire protection leaders, system architects, and decision-makers responsible for specifying and governing the use of hydraulic modelling tools. For engineering managers and design leads, the strong influence of perceived accuracy and layout quality has indicated that procurement and tool-selection decisions should not only consider licensing cost or brand familiarity, but also the transparency and robustness of the underlying hydraulic engine and the richness of layout and reporting features. Investing in tools that provide clear feedback on remote area selection, pressure margins, and sensitivity to design changes is likely to enhance practitioners' confidence and support more efficient designs. For those in governance roles such as corporate fire safety directors or technical authorities within large organizations the role of usability and expertise has suggested that formal training programmes and mentoring structures have been essential. Even a technically advanced tool may yield sub-optimal outcomes if user interfaces are cumbersome or if staff have not been supported in developing modelling proficiency. Structured training on hydraulic principles, friction models, and pressure-dependent demand formulations, combined with internal standards on data collection and documentation, can directly support the determinants that this study has shown to matter for perceived efficiency. For authorities having jurisdiction and policy-shaping bodies, the link between layout quality, data quality, and efficiency has implied that guidance documents and review checklists should explicitly address modelling assumptions, data sources (e.g., flow tests, hazard classifications), and design-area choices rather than focusing solely on rule-of-thumb calculations. In short, practitioners responsible for "architecting" fire protection strategies at organizational or jurisdictional levels have been able to use these findings as a roadmap: prioritize accurate, transparent tools; support user training; enforce high data standards; and integrate modelling outputs into a disciplined design review process.

**Figure 10: Integrated Multi-Layer Discussion Model**




Theoretically, the study has refined and extended an emerging "pipeline" perspective that links hydraulic modelling engines, user perceptions, and system-level safety outcomes. Prior work on hydraulic modelling has largely focused on algorithmic performance, numerical stability, and network-level technical metrics such as pressure distributions, resilience indices, or uniformity coefficients (Luvizotto et al., 2013). In parallel, fire safety research has addressed sprinkler reliability, activation dynamics, and fire-level performance metrics without always explicitly connecting these to the design and modelling processes that precede installation (Frank et al., 2013). The conceptual framework used here has brought these strands together by treating hydraulic modelling tools as an intermediate layer in a socio-technical pipeline: design inputs and tool characteristics have shaped user perceptions of accuracy, usability, and quality, which have in turn influenced perceived system efficiency and, by implication, resilience. The empirical confirmation that a set of perceived tool and user factors has explained a majority of the variance in perceived efficiency has provided quantitative support for this integrated view. Moreover, by operationalizing efficiency as a multi-component construct analogous to composite indices used in irrigation or resilience studies (García Bandala et al., 2022) the research has suggested that future theoretical work in fire engineering can benefit from explicit composite measures of sprinkler performance that blend hydraulic adequacy, design quality, reliability, and operational practicality. In doing so, it has moved beyond binary notions of "sprinklers present or absent" toward a more nuanced understanding of how the modelling and design pipeline contributes to graded levels of efficiency and resilience.

At the same time, the study has had several limitations that have needed to be acknowledged when interpreting the discussion and its implications. First, the research has been cross-sectional and perception-based: all variables, including sprinkler system efficiency, have been measured using self-reported Likert-scale items rather than objective performance data such as measured pressures, flows, or post-fire outcomes. Although the constructs have shown good reliability and have been grounded in prior literature, the results have reflected practitioners' subjective experiences and beliefs rather than directly observed system behavior. Second, sampling has been purposive and non-probabilistic, relying on professional networks, firms, and associations willing to circulate the survey. This approach has been appropriate for reaching experienced hydraulic modelers, but it has limited the generalizability of the findings; the sample may have under-represented smaller firms, regions with different regulatory contexts, or practitioners who rely minimally on modelling tools. Third, the study has focused on perceived characteristics of tools in general rather than on specific software products or algorithmic implementations. While this has allowed broader conceptual conclusions, it has meant that differences between solver types, friction-loss formulations, and pressure-dependent options have not been linked to individual tools. Finally, the analysis has inferred connections between perceived efficiency and real-world performance by analogy to prior experimental and reliability studies (e.g., Butry, 2012; Moinuddin et al., 2019; Ingason et al., 2022) rather than by directly pairing survey data with system-level outcome records. These limitations have not invalidated the findings, but they have indicated that results should be interpreted as characterizing perceived, practice-based relationships rather than as establishing causal effects on measured fire outcomes.

These limitations have pointed naturally toward several promising avenues for future research. One direction has been to integrate perception-based surveys like the present study with objective performance data, for example by collecting detailed design and hydraulic calculation records from completed projects and linking them to commissioning tests, impairment records, or, where available, post-incident performance. Such work could examine whether higher perceived accuracy and layout quality have corresponded systematically to larger hydraulic safety margins, fewer design revisions, or better outcomes in fire events. Another direction has involved comparative studies of specific hydraulic modelling tools and configurations, evaluating how differences in solver algorithms, friction models, and pressure-dependent features have affected both user perceptions and calculated performance metrics (Dem, 2018). There is also scope for extending the conceptual framework into a longitudinal or intervention-based design for example, assessing changes in perceptions and design outcomes before and after the introduction of a new modelling platform, structured training programme, or data-quality policy. On the theoretical side, future research could deepen the integration of technology acceptance, information-quality, and resilience concepts by testing structural equation models that link tool characteristics, acceptance constructs, and multi-dimensional efficiency or resilience indices (Dwivedi et al., 2017). Finally, qualitative studies involving interviews or focus groups with designers, installers, and authorities having jurisdiction could enrich understanding of contextual factors such as organizational culture, client expectations, and regulatory practices that shape how hydraulic modelling tools are selected, used, and trusted. By combining these quantitative and qualitative approaches, future work has the potential to build a more comprehensive, empirically grounded picture of the role that hydraulic modelling tools play in delivering efficient and resilient fire sprinkler systems.

**CONCLUSION**

This study has set out to quantitatively assess how hydraulic modeling tools have been associated with fire sprinkler system efficiency in real-world design and practice, and its results have provided clear, statistically grounded answers to that central question. Using a cross-sectional, case-study–based survey of 180 practitioners who have actively used hydraulic modeling tools in sprinkler work, the research has developed and applied reliable Likert-scale measures of perceived hydraulic accuracy, usability, user expertise, input data quality, layout quality, and overall sprinkler system efficiency. The analysis has shown that respondents have generally held favorable views of the tools they have used, with mean scores for all constructs lying above the neutral midpoint and perceived efficiency achieving the highest average. Reliability testing has confirmed that each construct has been measured with strong internal consistency, and correlation analysis has demonstrated that all tool- and user-related variables have been positively and significantly associated with perceived efficiency. Multiple regression modeling has further revealed that perceived hydraulic accuracy and layout quality have been the strongest predictors of efficiency, while usability, data quality, and user expertise have contributed additional significant explanatory power, together accounting for approximately 62% of the variance in perceived sprinkler system efficiency. In doing so, the study has successfully met its objectives: it has described practitioners' perceptions of hydraulic modeling tools, it has identified key determinants of perceived sprinkler system efficiency, and it has produced a predictive model that has empirically connected these determinants to efficiency outcomes. Conceptually, the research has integrated insights from hydraulic network modeling, sprinkler performance studies, and technology-acceptance theory, and it has proposed an integrated framework that has treated hydraulic modeling tools as a critical socio-technical link between design inputs and system-level performance. Practically, the findings have implied that organizations seeking to optimize sprinkler system efficiency have needed to prioritize accurate, transparent modeling engines, support user training to raise modeling expertise, enforce robust data and documentation standards, and select or configure tools that have facilitated high-quality layouts and usable workflows. At the same time, the study has acknowledged that its conclusions have been based on perceptions rather than direct performance measurements and that its purposive sample has limited strict generalization to all jurisdictions and practice settings. Nonetheless, by systematically capturing and analyzing the views of experienced practitioners across a range of roles and organizations, the research has provided a robust empirical foundation for understanding how hydraulic modeling tools have contributed to efficient fire sprinkler system design and has laid out a clear agenda for future work that has combined perception-based surveys, objective performance data, and more detailed comparative evaluations of specific modeling platforms and methods.

**RECOMMENDATIONS**

Based on the findings of this study, several practical recommendations can be made for engineering organizations, practitioners, software vendors, and regulators who aim to enhance fire sprinkler system efficiency through the effective use of hydraulic modeling tools. First, organizations should formally prioritize tool accuracy and transparency when selecting or standardizing on hydraulic modeling software; procurement decisions should explicitly evaluate how clearly each tool represents friction-loss models, pressure margins, remote-area calculations, and underlying assumptions, and preference should be given to platforms that provide traceable calculation reports rather than opaque "black-box" outputs. Second, because perceived layout quality has emerged as a key driver of efficiency, design teams should institutionalize structured workflows in which hydraulic modeling and layout development are tightly integrated: for example, by adopting model-based design procedures where head spacing, pipe routing, and zoning are iteratively refined based on real-time hydraulic feedback instead of being treated as separate, sequential steps. Third, firms should invest systematically in training and professional development focused on both hydraulic principles and advanced tool usage; this includes onboarding programmes for junior designers, refresher courses for mid-career staff, and mentoring structures in which highly experienced modelers review, coach, and approve complex designs, thereby raising the overall level of user expertise that has been shown to influence perceived system efficiency. Fourth, consistent with the importance of data quality, organizations should adopt clear internal standards and checklists for collecting, documenting, and validating key inputs such as water supply test data, hazard classifications, roughness coefficients, and design criteria and should require that each project maintain a "data sheet" that is reviewed and signed off before detailed modeling proceeds. Fifth, technical leaders should promote a culture of critical review in which hydraulic models and sprinkler layouts are routinely subjected to peer review or internal design audits that probe assumptions, test alternate scenarios, and verify that safety margins remain adequate under supply variations and plausible impairments; this not only improves design robustness but also reinforces user trust in modeling outputs. Sixth, software vendors should respond to these findings by enhancing usability and support features including intuitive interfaces, context-sensitive help, validation warnings, and educational resources so that tools better match the workflows of fire protection engineers and reduce the cognitive load associated with complex modeling tasks. Finally, regulators and authorities having jurisdiction should consider incorporating explicit references to hydraulic modeling quality into guidance documents and review practices, encouraging submittals that include not only demand summaries but also evidence of appropriate modeling assumptions, input data sources, and sensitivity checks. By acting on these recommendations, stakeholders across the fire protection ecosystem can align tool capabilities, user skills, and data practices in ways that systematically reinforce one another, thereby increasing the likelihood that hydraulic modeling tools are not only widely used but also consistently leveraged to deliver efficient, reliable, and resilient fire sprinkler systems in practice.

**LIMITATIONS**

This study has had several limitations that have needed to be acknowledged when interpreting its findings and applying its conclusions to practice. First, the research has relied entirely on a cross-sectional survey using self-reported data collected at a single point in time, which has meant that all constructs including perceived sprinkler system efficiency have been measured as subjective judgments rather than as objective performance indicators derived from flow tests, commissioning measurements, or post-fire investigations. As a result, the relationships that have been identified among hydraulic accuracy, usability, expertise, data quality, layout quality, and efficiency have reflected how practitioners have *perceived* these factors rather than how systems have demonstrably performed in real incidents, and causal directions have not been empirically established. Second, the study has used a non-probability purposive sampling approach, drawing respondents mainly through professional networks, firms, and associations that have been willing to disseminate the survey. While this strategy has been appropriate for reaching practitioners with direct experience of hydraulic modelling, it has limited strict statistical generalizability, and the sample may have over-represented organizations that have already invested in modelling tools and under-represented smaller firms, less-resourced regions, or practitioners who have relied more on manual methods. Third, the research has treated "hydraulic modelling tools" at a relatively aggregated level, capturing perceptions of accuracy and usability across whatever tools respondents have used, rather than differentiating between specific software platforms, solver algorithms, or pressure-dependent options. This has meant that the study has not identified which particular features or implementations have driven higher or lower perceptions, nor has it compared brands or versions in a controlled way. Fourth, the reliance on Likert's five-point scales has introduced the possibility of common method bias and response tendencies such as central tendency or social desirability, even though scale reliability has been shown to be high; all variables have been collected from the same respondents using the same instrument, which has potentially inflated observed associations. Fifth, the model has focused primarily on individual-level perceptions and has not explicitly captured important organizational, regulatory, and cultural factors, such as company design culture, client expectations, or local enforcement practices, all of which have likely shaped both tool adoption and design outcomes. Finally, the quantitative design has not incorporated qualitative insights from interviews, focus groups, or document analysis that might have provided richer explanation of why certain tools have been viewed as more accurate or usable, or how specific project experiences have influenced efficiency judgments. Together, these limitations have not invalidated the study's contributions, but they have indicated that the results should be interpreted as a statistically coherent picture of practitioners' perceptions within the sampled contexts, rather than as a definitive or exhaustive account of all factors affecting the real-world performance and reliability of hydraulically modelled fire sprinkler systems.

## REFERENCES


[1]. Abdelbaki, C., Benchaib, M. M., Benziada, S., & others. (2017). Management of a water distribution network by coupling GIS and hydraulic modeling: A case study of Chetouane in Algeria. *Applied Water Science*, *7*, 1561–1567. https://doi.org/10.1007/s13201-016-0416-1

[2]. Abdul, H. (2023). Artificial Intelligence in Product Marketing: Transforming Customer Experience And Market Segmentation. *ASRC Procedia: Global Perspectives in Science and Scholarship*, *3*(1), 132–159. https://doi.org/10.63125/58npbx97

[3]. Abdulla, M., & Md. Wahid Zaman, R. (2023). Quantitative Study On Workflow Optimization Through Data Analytics In U.S. Digital Enterprises. *American Journal of Interdisciplinary Studies*, *4*(03), 136–165. https://doi.org/10.63125/y2qshd31

[4]. Adham, A., Riksen, M., Abed, R., & others. (2022). Assessing suitable techniques for rainwater harvesting using analytical hierarchy process (AHP) and GIS techniques. *Water*, *14*(13), 2110. https://doi.org/10.3390/w14132110

[5]. Ahmadullah, R., & Kang, D. (2016). Designing of hydraulically balanced water distribution network based on GIS and EPANET. *International Journal of Advanced Computer Science and Applications*, *7*(2), 118–125. https://doi.org/10.14569/ijacsa.2016.070216

[6]. Al-Hajj, S., Desapriya, E., Pawliuk, C., Garis, L., & Pike, I. (2022). Interventions for preventing residential fires in vulnerable neighbourhoods and Indigenous communities: A systematic review of the literature. *International Journal of Environmental Research and Public Health*, *19*(9), 5434. https://doi.org/10.3390/ijerph19095434

[7]. Arfan, U., Sai Praveen, K., & Alifa Majumder, N. (2021). Predictive Analytics For Improving Financial Forecasting And Risk Management In U.S. Capital Markets. *American Journal of Interdisciplinary Studies*, *2*(04), 69–100. https://doi.org/10.63125/tbw49w69

[8]. Ateş, S. (2016). Hydraulic modelling of closed pipes in loop equations of water distribution networks. *Applied Mathematical Modelling*, *40*(2), 966–983. https://doi.org/10.1016/j.apm.2015.06.017

[9]. Atukunda, A., Ibrahim, M. G., Fujii, M., & others. (2022). Dual biogas/biochar production from anaerobic co-digestion of petrochemical and domestic wastewater: A techno-economic and sustainable approach. *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-022-02944-w

[10]. Avila-Melgar, E. Y., Cruz-Chávez, M. A., & Martinez-Bahena, B. (2017). General methodology for using EPANET as an optimization element in evolutionary algorithms in a grid computing environment for water distribution network design. *Water Science and Technology: Water Supply*, *17*(1), 39–51. https://doi.org/10.2166/ws.2016.101

[11]. Ayad, A., Awad, H., & Yassin, A. (2013). Developed hydraulic simulation model for water pipeline networks. *Alexandria Engineering Journal*, *52*(1), 43–49. https://doi.org/10.1016/j.aej.2012.11.005

[12]. Baskaran, V., & Velkennedy, R. (2022). A systematic review on the role of geographical information systems in monitoring and achieving Sustainable Development Goal 6: Clean water and sanitation. *Sustainable Development*, *30*(6), 1417–1425. https://doi.org/10.1002/sd.2302

[13]. Butry, D. T. (2012). Comparing the performance of residential fire sprinklers with other life-safety technologies. *Accident Analysis & Prevention*, *48*, 480–494. https://doi.org/10.1016/j.aap.2012.03.006

[14]. Cablé, A., Chetehouna, K., Gascoin, N., Settar, A., Van Herpe, K., & Kadoche, M. (2019). Experimental and numerical study of sprinkler fire protection systems: Effect of initial pressure on system performance. *Journal of Loss Prevention in the Process Industries*, *60*, 176–187. https://doi.org/10.1016/j.jlp.2019.04.009

[15]. Croce, P., Beyler, C., Dubay, C., Johnson, P., & McNamee, M. (2020). Fast-response sprinkler technology: Hsiang-Cheng Kung, Gunnar Heskestad, Robert Bill, Roger Allard: The 2019 Phillip J. DiNenno Prize. *Fire Technology*, *56*, 1981–2001. https://doi.org/10.1007/s10694-020-00961-7

[16]. Croce, P. A., Grosshandler, W. L., Bukowski, R. W., & Gritzo, L. A. (2008). The international FORUM of fire research directors: A position paper on performance-based design for fire code applications. *Fire Safety Journal*, *43*(3), 234–236. https://doi.org/10.1016/j.firesaf.2007.12.004

[17]. Dem, S. (2018). Evaluation of the suitability of global gradient algorithm and inverse matrix method for steady-state analysis of water distribution networks. *Ngumehu Journal*, *7*, 23–33. https://doi.org/10.28948/ngumuh.383777

[18]. Dwivedi, Y. K., Rana, N. P., Jeyaraj, A., Clement, M., & Williams, M. D. (2017). Re-examining the unified theory of acceptance and use of technology (UTAUT): Towards a revised theoretical model. *Information Systems Frontiers*, *19*(3), 1–16. https://doi.org/10.1007/s10796-017-9774-y

[19]. Dwivedi, Y. K., Rana, N. P., Tamilmani, K., Raman, R., & others. (2020). A meta-analysis based modified unified theory of acceptance and use of technology (meta-UTAUT): A review of emerging literature. *Current Opinion in Psychology*, *36*, 13–18. https://doi.org/10.1016/j.copsyc.2020.03.008

[20]. Eck, B. J., & Mevissen, M. (2015). Quadratic approximations for pipe friction. *Journal of Hydroinformatics*, *17*(3), 462–472. https://doi.org/10.2166/hydro.2014.170

[21]. Eryürük, K. (2021). Hydraulic models for calculating head loss in water distribution system: A case study in Konya. *Avrupa Bilim ve Teknoloji Dergisi*, *28*, 275–279. https://doi.org/10.31590/ejosat.996991

[22]. Ferdous Ara, A. (2021). Integration Of STI Prevention Interventions Within PrEP Service Delivery: Impact On STI Rates And Antibiotic Resistance. *International Journal of Scientific Interdisciplinary Research*, *2*(2), 63–97. https://doi.org/10.63125/65143m72

[23]. Ferdous Ara, A., & Beatrice Onyinyechi, M. (2023). Long-Term Epidemiologic Trends Of STIs PRE- and POST-PrEP Introduction: A National Time-Series Analysis. *American Journal of Health and Medical Sciences*, *4*(02), 01–35. https://doi.org/10.63125/mp153d97

[24]. Frank, K., Gravestock, N., Spearpoint, M., & Fleischmann, C. (2013). A review of sprinkler system effectiveness studies. *Fire Science Reviews*, *2*(6). https://doi.org/10.1186/2193-0414-2-6

[25]. Garber, R. I. (2009). Fire sprinkler heads, design, and failure. *Journal of Failure Analysis and Prevention*, *9*(5), 495–498. https://doi.org/10.1007/s11668-009-9296-0

[26]. García Bandala, M., Robles Rovelo, C. O., Bautista-Capetillo, C., González-Trinidad, J., Júnez-Ferreira, H. E., Servín Palestina, M., Pineda Martínez, H., Morales de Avila, H., & Rivas Recendez, M. I. (2022). Analysis of irrigation performance of a solid-set sprinkler irrigation system at different experimental conditions. *Water*, *14*(17), 2641. https://doi.org/10.3390/w14172641

[27]. Hajibabaei, M., Nazif, S., & Sitzenfrei, R. (2019). Improving the performance of water distribution networks based on the value index in the system dynamics framework. *Water*, *11*(12), 2445. https://doi.org/10.3390/w11122445

[28]. Hauptmanns, U., Marx, M., & Grünbeck, S. (2008). Availability analysis for a fixed wet sprinkler system. *Fire Safety Journal*, *43*, 468–476. https://doi.org/10.1016/j.firesaf.2008.03.002

[29]. Himoto, K. (2020). Conceptual framework for quantifying fire resilience – A new perspective on fire safety performance of buildings. *Fire Safety Journal*, *120*, 103052. https://doi.org/10.1016/j.firesaf.2020.103052

[30]. Ho, K.-F., Ho, C.-H., & Chung, M.-H. (2019). Theoretical integration of user satisfaction and technology acceptance of the nursing process information system. *PLOS ONE*, *14*(6), e0217622. https://doi.org/10.1371/journal.pone.0217622

[31]. Holden, R. J., & Karsh, B.-T. (2010). The technology acceptance model: Its past and its future in health care. *Journal of Biomedical Informatics*, *43*(1), 159–172. https://doi.org/10.1186/1472-6947-10-159

[32]. Hossain, M. B., Roy, N. C., Biswas, P. C., Azad, M. N., & Yusuf, E. (2021). Analysis and design of water distribution network using EPANET: A case study of HSTU campus of Dinajpur, Bangladesh. *Hydrology*, *9*(2), 36–47. https://doi.org/10.11648/j.hyd.20210902.12

[33]. Ibrahim, G. R. F., Rasul, A., Hamid, A. A., & others. (2019). Suitable site selection for rainwater harvesting and storage: Case study using Dohuk governorate. *Water*, *11*(4), 864. https://doi.org/10.3390/w11040864

[34]. Ingason, H., Li, Y. Z., Arvidson, M., & Jiang, L. (2022). Fire tests with automatic sprinklers in an intermediate scale tunnel. *Fire Safety Journal*, *129*, 103567. https://doi.org/10.1016/j.firesaf.2022.103567

[35]. Jahid, M. K. A. S. R. (2021). Digital Transformation Frameworks For Smart Real Estate Development In Emerging Economies. *Review of Applied Science and Technology*, *6*(1), 139–182. https://doi.org/10.63125/cd09ne09

[36]. Jaiswal, A. K., Thakur, P. K., Kumar, P., & Kannaujiya, S. (2021). Geospatial modeling of water supply distribution system: A case study of Dehradun city, India. *H2Open Journal*, *4*, 393–412. https://doi.org/10.2166/h2oj.2021.118

[37]. Jebb, A. T., Ng, V., & Tay, L. (2021). A review of key Likert scale development advances: 1995–2019. *Frontiers in Psychology*, *12*, 637547. https://doi.org/10.3389/fpsyg.2021.637547

[38]. Jha, K., & Mishra, M. K. (2020). Object-oriented integrated algorithms for efficient water pipe network by modified Hardy Cross technique. *Journal of Computational Design and Engineering*, *7*(1), 56–64. https://doi.org/10.1093/jcde/qwaa006

[39]. Joshi, A., Kale, S., Chandel, S., & Pal, D. K. (2015). Likert scale: Explored and explained. *British Journal of Applied Science & Technology*, *7*(4), 396–403. https://doi.org/10.9734/bjast/2015/14975

[40]. Khan, S., Katoen, J.-P., Volk, M., Zafar, A., & Sher, F. (2021). *Modelling and analysis of fire sprinklers by verifying dynamic fault trees* 2021 IEEE Latin-American Symposium on Dependable Computing (LADC),

[41]. Khoat, H. T., Kim, J. T., Quoc, T. D., Kwark, J. H., & Ryou, H. S. (2020). A numerical analysis of the fire characteristics after sprinkler activation in the compartment fire. *Energies*, *13*(12), 3099. https://doi.org/10.3390/en13123099

[42]. King, W. R., & He, J. (2006). A meta-analysis of the technology acceptance model. *Information & Management*, *43*(6), 740–755. https://doi.org/10.1016/j.im.2006.05.003

[43]. Luvizotto, E., Cavichia, M. C., Vatavuk, P., & Andrade, J. G. P. (2013). Nonmatrix gradient method for the simulation of water distribution networks. *Journal of Water Resources Planning and Management*, *139*(4), 433–439. https://doi.org/10.1061/(asce)wr.1943-5452.0000271

[44]. Marangunić, N., & Granić, A. (2015). Technology acceptance model: A literature review from 1986 to 2013. *Universal Access in the Information Society*, *14*, 81–95. https://doi.org/10.1007/s10209-014-0348-1

[45]. Md Al Amin, K., & Md Mesbaul, H. (2023). Smart Hybrid Manufacturing: A Combination Of Additive, Subtractive, And Lean Techniques For Agile Production Systems. *Journal of Sustainable Development and Policy*, *2*(04), 174-217. https://doi.org/10.63125/7rb1zz78

[46]. Md Ariful, I., & Efat Ara, H. (2022). Advances And Limitations Of Fracture Mechanics–Based Fatigue Life Prediction Approaches For Structural Integrity Assessment: A Systematic Review. *American Journal of Interdisciplinary Studies*, *3*(03), 68-98. https://doi.org/10.63125/fg8ae957

[47]. Md Arman, H., & Md.Kamrul, K. (2022). A Systematic Review of Data-Driven Business Process Reengineering And Its Impact On Accuracy And Efficiency Corporate Financial Reporting. *International Journal of Business and Economics Insights*, *2*(4), 01–41. https://doi.org/10.63125/btx52a36

[48]. Md Foysal, H., & Aditya, D. (2023). Smart Continuous Improvement With Artificial Intelligence, Big Data, And Lean Tools For Zero Defect Manufacturing Systems. *American Journal of Scholarly Research and Innovation*, *2*(01), 254–282. https://doi.org/10.63125/6cak0s21

[49]. Md Hamidur, R. (2023). Thermal & Electrical Performance Enhancement Of Power Distribution Transformers In Smart Grids. *American Journal of Scholarly Research and Innovation*, *2*(01), 283–313. https://doi.org/10.63125/n2p6y628

[50]. Md Harun-Or-Rashid, M., Mst. Shahrin, S., & Sai Praveen, K. (2023). Integration Of IOT And EDGE Computing For Low-Latency Data Analytics In Smart Cities And IOT Networks. *Journal of Sustainable Development and Policy*, *2*(03), 01-33. https://doi.org/10.63125/004h7m29

[51]. Md Mesbaul, H., & Md. Tahmid Farabe, S. (2022). Implementing Sustainable Supply Chain Practices In Global Apparel Retail: A Systematic Review Of Current Trends. *ASRC Procedia: Global Perspectives in Science and Scholarship*, *2*(1), 332–363. https://doi.org/10.63125/nen7vd57

[52]. Md Musfiqur, R., & Md.Kamrul, K. (2023). Mechanisms By Which AI-Enabled Crm Systems Influence Customer Retention And Overall Business Performance: A Systematic Literature Review Of Empirical Findings. *International Journal of Business and Economics Insights*, *3*(1), 31-67. https://doi.org/10.63125/qqe2bm11

[53]. Md Muzahidul, I., & Md Mohaiminul, H. (2023). Explainable AI (XAI) Models For Cloud-Based Business Intelligence: Ensuring Compliance And Secure Decision-Making. *American Journal of Interdisciplinary Studies*, *4*(03), 208–249. https://doi.org/10.63125/5etfhh77

[54]. Md Nahid, H. (2022). Statistical Analysis of Cyber Risk Exposure And Fraud Detection In Cloud-Based Banking Ecosystems. *ASRC Procedia: Global Perspectives in Science and Scholarship*, *2*(1), 289–331. https://doi.org/10.63125/9wf91068

[55]. Md Sarwar Hossain, S., & Md Milon, M. (2022). Machine Learning-Based Pavement Condition Prediction Models For Sustainable Transportation Systems. *American Journal of Interdisciplinary Studies*, *3*(01), 31–64. https://doi.org/10.63125/1jsmkg92

[56]. Md. Abdur, R., & Zamal Haider, S. (2022). Assessment Of Data-Driven Vendor Performance Evaluation In Retail Supply Chains Analyzing Metrics, Scorecards, And Contract Management Tools. *Journal of Sustainable Development and Policy*, *1*(04), 71-116. https://doi.org/10.63125/2a641k35

[57]. Md. Al Amin, K., & Sai Praveen, K. (2023). The Role Of Industrial Engineering In Advancing Sustainable Manufacturing And Quality Compliance In Global Engineering Systems. *International Journal of Scientific Interdisciplinary Research*, *4*(4), 31–61. https://doi.org/10.63125/8w1vk676

[58]. Md. Hasan, I., & Ashraful, I. (2023). The Effect Of Production Planning Efficiency On Delivery Timelines In U.S. Apparel Imports. *Journal of Sustainable Development and Policy*, *2*(04), 35-73. https://doi.org/10.63125/sg472m51

[59]. Md. Jobayer Ibne, S., & Md. Kamrul, K. (2023). Automating NIST 800-53 Control Implementation: A Cross-Sector Review Of Enterprise Security Toolkits. *ASRC Procedia: Global Perspectives in Science and Scholarship*, *3*(1), 160–195. https://doi.org/10.63125/prkw8r07

[60]. Md.Akbar, H., & Farzana, A. (2021). High-Performance Computing Models For Population-Level Mental Health Epidemiology And Resilience Forecasting. *American Journal of Health and Medical Sciences*, *2*(02), 01–33. https://doi.org/10.63125/k9d5h638

[61]. Mohammad Mushfequr, R., & Ashraful, I. (2023). Automation And Risk Mitigation in Healthcare Claims: Policy And Compliance Implications. *Review of Applied Science and Technology*, *2*(04), 124–157. https://doi.org/10.63125/v73gyg14

[62]. Mohammad Mushfequr, R., & Sai Praveen, K. (2022). Quantitative Investigation Of Information Security Challenges In U.S. Healthcare Payment Ecosystems. *International Journal of Business and Economics Insights*, *2*(4), 42–73. https://doi.org/10.63125/gcg0fs06

[63]. Moinuddin, K., Thomas, I., & Chea, S. (2009). Estimating the reliability of sprinkler systems in Australian high-rise office buildings. *Fire Safety Science*, *9*, 515–526. https://doi.org/10.3801/iafss.Fss.9-515

[64]. Moinuddin, K. A. M., Innocent, J., & Keshavarz, K. (2019). Reliability of sprinkler system in Australian shopping centres: A fault tree analysis. *Fire Safety Journal*, *105*, 204–215. https://doi.org/10.1016/j.firesaf.2019.03.006

[65]. Moinuddin, K. A. M., Thomas, I. R., & Chea, S. (2008). Estimating the reliability of sprinkler systems in Australian high-rise office buildings. *Fire Safety Science*, *9*, 515–526. https://doi.org/10.3801/iafss.Fss.9-515

[66]. Mortuza, M. M. G., & Rauf, M. A. (2022). Industry 4.0: An Empirical Analysis of Sustainable Business Performance Model Of Bangladeshi Electronic Organisations. *International Journal of Economy and Innovation*. https://gospodarkainnowacje.pl/index.php/issue_view_32/article/view/826

[67]. Muranho, J., Ferreira, A., Sousa, J., Gomes, A., & Sá Marques, A. (2014). Technical performance evaluation of water distribution networks based on EPANET. *Procedia Engineering*, *70*, 1201–1210. https://doi.org/10.1016/j.proeng.2014.02.133

[68]. Muranho, J., Ferreira, A., Sousa, J., Gomes, A., & Sá Marques, A. (2020). Pressure-driven simulation of water distribution networks: Searching for numerical stability. *Environmental Sciences Proceedings*, *2*(1), 48. https://doi.org/10.3390/environsciproc2020002048

[69]. Pankaz Roy, S., & Md. Kamrul, K. (2023). HACCP and ISO Frameworks For Enhancing Biosecurity In Global Food Distribution Chains. *American Journal of Scholarly Research and Innovation*, *2*(01), 314–356. https://doi.org/10.63125/9pbp4h37

[70]. Petter, S., DeLone, W., & McLean, E. (2008). Measuring information systems success: Models, dimensions, measures, and interrelationships. *European Journal of Information Systems*, *17*(3), 236–263. https://doi.org/10.1057/ejis.2008.15

[71]. Rakibul, H., & Samia, A. (2022). Information System-Based Decision Support Tools: A Systematic Review Of Strategic Applications In Service-Oriented Enterprises. *Review of Applied Science and Technology*, *1*(04), 26-65. https://doi.org/10.63125/w3cevz78

[72]. Reza, M., Vorobyova, K., & Rauf, M. (2021). The effect of total rewards system on the performance of employees with a moderating effect of psychological empowerment and the mediation of motivation in the leather industry of Bangladesh. *Engineering Letters*, *29*, 1-29.

[73]. Rony, M. A., & Ashraful, I. (2022). Big Data And Engineering Analytics Pipelines For Smart Manufacturing: Enhancing Efficiency, Quality, And Predictive Maintenance. *American Journal of Scholarly Research and Innovation*, *1*(02), 59–85. https://doi.org/10.63125/rze0my79

[74]. Saba, A., Shaikat, B., & Tonoy Kanti, C. (2023). Integration Of Artificial Intelligence And Advanced Computing To Develop Resilient Cyber Defense Systems. *Journal of Sustainable Development and Policy*, *2*(04), 74-107. https://doi.org/10.63125/rxyc6y88

[75]. Saba, A., & Tonoy Kanti, C. (2023). Explainable Artificial Intelligence (XAI) Approaches For Cyber Risk Assessment In Financial Services. *American Journal of Interdisciplinary Studies*, *4*(03), 96-135. https://doi.org/10.63125/3gjcb322

[76]. Saikat, S. (2021). Real-Time Fault Detection in Industrial Assets Using Advanced Vibration Dynamics And Stress Analysis Modeling. *American Journal of Interdisciplinary Studies*, *2*(04), 39–68. https://doi.org/10.63125/0h163429

[77]. Saikat, S. (2022). CFD-Based Investigation of Heat Transfer Efficiency In Renewable Energy Systems. *International Journal of Scientific Interdisciplinary Research*, *1*(01), 129–162. https://doi.org/10.63125/ttw40456

[78]. Schepers, J., & Wetzels, M. (2007). A meta-analysis of the technology acceptance model: Investigating subjective norm and moderation effects. *Information & Management*, *44*(1), 90–103. https://doi.org/10.1016/j.im.2006.10.007

[79]. Scherer, R., Siddiq, F., & Tondeur, J. (2019). The technology acceptance model (TAM): A meta-analytic structural equation modeling approach to explaining teachers' adoption of digital technology in education. *Computers & Education*, *128*, 13–35. https://doi.org/10.1016/j.compedu.2018.09.009

[80]. Shaikh, S., & Aditya, D. (2021). Federated Learning-Driven Predictive Quality Analytics and Supply Chain Optimization In Distributed Manufacturing Networks. *Review of Applied Science and Technology*, *6*(1), 74-107. https://doi.org/10.63125/k18cbz55

[81]. Shaikh, S., & Md. Tahmid Farabe, S. (2023). Digital Twin-Driven Process Modeling For Energy Efficiency And Lifecycle Optimization In Industrial Facilities. *American Journal of Interdisciplinary Studies*, *4*(03), 65–95. https://doi.org/10.63125/e4q64869

[82]. Shaikh, S., & Sudipto, R. (2022). Multi-Objective Thermo-Economic and Supply Chain Optimization Modeling For Hydrogen Energy Integration In Smart Factories. *International Journal of Scientific Interdisciplinary Research*, *1*(01), 163–193. https://doi.org/10.63125/p9y8p705

[83]. Siew, C., & Tanyimboh, T. (2012). Pressure-dependent EPANET extension. *Water Resources Management*, *26*(6), 1477–1498. https://doi.org/10.1007/s11269-011-9968-x

[84]. Thakre, S. B., & Thakur, P. (2015). Network analysis of water distribution system in rural areas using EPANET. *Procedia Engineering*, *119*, 496–505. https://doi.org/10.1016/j.proeng.2015.08.875

[85]. Tonoy Kanti, C., & Shaikat, B. (2021). Blockchain-Enabled Security Protocols Combined With AI For Securing Next-Generation Internet Of Things (IOT) Networks. *International Journal of Scientific Interdisciplinary Research*, *2*(2), 98–127. https://doi.org/10.63125/pcdqzw41

[86]. Venkatesh, V., & Bala, H. (2008). Technology acceptance model 3 and a research agenda on interventions. *Decision Sciences*, *39*(2), 273–315. https://doi.org/10.1111/j.1540-5915.2008.00192.x

[87]. Venkatesh, V., Thong, J. Y. L., & Xu, X. (2012). Consumer acceptance and use of information technology: Extending the unified theory of acceptance and use of technology. *MIS Quarterly*, *36*(1), 157–178. https://doi.org/10.2307/41410412

[88]. Vetter, M., Dinkov, I., Schelb, D., & Trimis, D. (2021). Experimental study on the effects of sprinkler activation on the stratified smoke layer inside a 36 $m^2$ compartment. *Fire Safety Journal*, *121*, 103313. https://doi.org/10.1016/j.firesaf.2021.103313

[89]. Wieczorek, C. J., Ditch, B., & Bill, R. G., Jr. (2011). Environmental impact of automatic fire sprinklers: Part 2. Experimental study. *Fire Technology*, *47*, 765–779. https://doi.org/10.1007/s10694-010-0192-7

[90]. Williams, M. D., Rana, N. P., & Dwivedi, Y. K. (2015). The unified theory of acceptance and use of technology (UTAUT): A literature review. *Journal of Enterprise Information Management*, *28*(3), 443–488. https://doi.org/10.1108/jeim-09-2014-0088

[91]. Wixom, B. H., & Todd, P. A. (2005). A theoretical integration of user satisfaction and technology acceptance. *Information Systems Research*, *16*(1), 85–102. https://doi.org/10.1287/isre.1050.0042

[92]. Xu, Z., Zhang, Z., Lu, X., Zeng, X., & Guan, H. (2018). Post-earthquake fire simulation considering overall seismic damage of sprinkler systems based on BIM and FEMA P-58. *Automation in Construction*, *90*, 9–22. https://doi.org/10.1016/j.autcon.2018.02.015

[93]. Zamal Haider, S., & Hozyfa, S. (2023). A Quantitative Study On IT-Enabled ERP Systems And Their Role In Operational Efficiency. *International Journal of Scientific Interdisciplinary Research*, *4*(4), 62–99. https://doi.org/10.63125/nbpyce10

[94]. Zhuiykov, S., & Dowling, V. P. (2005). Maintenance testing of sprinkler heads: Qualitative analysis causes of failures. *Fire Safety Science*, *8*, 811–822. https://doi.org/10.3801/iafss.Fss.8-811

[95]. Zobayer, E. (2021a). Data Driven Predictive Maintenance In Petroleum And Power Systems Using Random Forest Regression Model For Reliability Engineering Framework. *Review of Applied Science and Technology*, *6*(1), 108-138. https://doi.org/10.63125/5bjx6963

[96]. Zobayer, E. (2021b). Machine Learning Approaches For Optimization Of Lubricant Performance And Reliability In Complex Mechanical And Manufacturing Systems. *American Journal of Scholarly Research and Innovation*, *1*(01), 61–92. https://doi.org/10.63125/5zvkgg52

[97]. Zobayer, E. (2023). IOT Integration In Intelligent Lubrication Systems For Predictive Maintenance And Performance Optimization In Advanced Manufacturing Industries. *Journal of Sustainable Development and Policy*, *2*(04), 140-173. https://doi.org/10.63125/zybrmx69