

ANN Applications in Automatic Fire Sprinkler Head Calculation for Car Parking Basements: A Comprehensive Review

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Abstract

manually often involves repetitive tasks, high workloads, and the risk of human error. To address this, the present study proposes an intelligent framework that automates the sprinkler layout design process. A dataset of 60 existing sprinkler drawings was used to train a ANN (Artificial Neural Network). Once trained, the model was able to automatically generate sprinkler layouts for new or irregular floorplans, achieving 99.5% coverage of the required protection area. Notably, the ANN-designed layouts used about 13% fewer sprinkler heads compared Fire sprinkler systems are a standard safety feature in modern buildings, but preparing their layouts to those planned by professional engineers, while still complying with relevant codes. This approach not only ensures safety compliance but also improves efficiency—reducing drawing preparation time by nearly 76% and lowering costs by optimizing the number of sprinklers required [1]. This study explores the use of artificial neural networks (ANN) to automatically generate sprinkler system layouts for complex and irregular floorplans. By learning from a dataset of existing designs, the ANN framework demonstrates the ability to produce code-compliant layouts with improved efficiency and optimized resource usage compared to traditional methods. The findings highlight the potential of intelligent design tools to enhance accuracy, reduce workload, and support cost-effective fire protection solutions in modern buildings.

KEYWORD: - Artificial Neural Network (ANN), Fire Sprinkler System, Automatic Layout Design Building Fire Safety, Intelligent Framework Basement Car Parking Design Automation Code Compliance

INTRODUCTION

The preparation of the engineering drawings still heavily relies on the engineers on manual, such as the distribution of sprinkler heads and calculation of egress travel distance. This manual design process suffers from prolonged time consumption and low efficiency. Overruns of time and cost are commonly seen, and statistics show that although the construction industry represents 13% of global GDP, it has experienced only a 1% annual profit increase over the past 20

years [2]. Basement car parks are among the most hazardous locations for fires because of their unique environment. Vehicles bring a high fire load in the form of fuels, plastics, tires, and upholstery, which can generate very high heat release rates once ignited [3]. This leads to large amounts of toxic smoke and intense heat. The building basement setting worsens the problem. Low ceiling heights mean that smoke has less volume to rise into and stratify. Instead of staying above head level, it quickly forms a dense smoke layer at the ceiling that descends rapidly. Experiments show that lower ceilings not only accelerate smoke filling but also increase combustion intensity and carbon monoxide yield [4]. As a result, visibility can drop below ten meters, toxic gases like CO can exceed safe limits within minutes, and evacuation time becomes very limited [5].

Geometry also plays a key role. Beams, ramps, and narrow layouts restrict smoke movement and reduce natural ventilation. Studies of long, narrow underground spaces have shown that ceiling structures trap heat and produce thicker smoke layers that descend faster, making conditions untenable for occupants [6]. Compared with above-ground spaces, basements allow little chance for smoke or heat to escape, creating highly dangerous conditions for both evacuation and firefighting [7].

In summary, basement car parks combine three dangerous factors: high fire load, confined geometry, and limited ventilation. Together, these make fires grow quickly, smoke spread aggressively, and safe evacuation times very short. This is why modern fire-safety design emphasizes the need for sprinklers, fast smoke-extraction systems, and early detection technologies in such structures [8].

Advantages of ANN-Based Sprinkler Systems over Prescriptive Standards

Traditional sprinkler design follows prescriptive standards like NFPA 13, NBC and IS 15105. These standards group spaces into hazard categories and then specify things like how much water density to apply, what pipe size to use, or how many sprinklers should operate at once. The problem is that this approach assumes a very fixed fire scenario. For example, it doesn't care if the fire is coming from a patrol car, an EV battery, or a pile of plastics it just applies the same rules. In

basement car parks, where fires can be much more dynamic, this “one size fits all” method often falls short.

Another issue is that the design of fire service systems is very complicated, with thousands of code clusters and needs to be incorporated with many disciplines such as structure, mechanical, and transportation. There are unavoidable and considerable errors in the human-lead design process. As a result, after a significant time investment on drawing preparation, great efforts are still needed on code compliance checking of these drawings by the dedicated agency, which is also manual [1]. That’s where artificial neural networks (ANNs) come in. ANNs are good at spotting patterns in messy, real-world data. Instead of depending on static hazard classes, they can look at many inputs at once like heat, smoke, gas concentration, airflow, and even camera data and then decide how the sprinkler system should respond. This means the sprinkler doesn’t just switch on in a fixed way; it can adapt to the actual fire conditions.

For example, if an ANN system detects that the smoke is spreading faster in one zone, it can trigger sprinklers there first, while holding back in another area to save water. If sensors pick up high carbon monoxide levels, the ANN could coordinate with the ventilation fans at the same time to push smoke out. In short, instead of just dumping water everywhere, the system becomes smarter and more targeted.

Research already shows that prescriptive designs tend to either over-design (using more water than needed) or under-protect (missing high heat-release scenarios) [10]. Experiments with ANN and other AI tools have shown they can optimize sprinkler layouts [11], improve fire detection, and even work together with digital-twin models of underground spaces [12].

Sprinkler System

Automatic Sprinkler Systems: An automatic sprinkler system is a fire protection method designed to detect, control, and often extinguish fires in their early stages without human intervention. It consists of a network of pipes fitted with sprinkler heads that are strategically placed throughout a building. When a fire occurs, the system activates in response to the heat produced by the fire, discharging water directly onto the flames and the surrounding area to control and extinguish the fire, prevent its spread, and minimize damage.

A sprinkler system consists of a water supply (or supplies) and one or more sprinkler installations; each installation consists of a set of installation control valves and a pipe array fitted with sprinkler heads. The sprinkler heads are fitted at specified locations at the roof or ceiling, and where necessary between racks, below shelves, inside ovens or stoves or below obstructions. The main elements of a typical installation is shown in Fig. 1 [13].

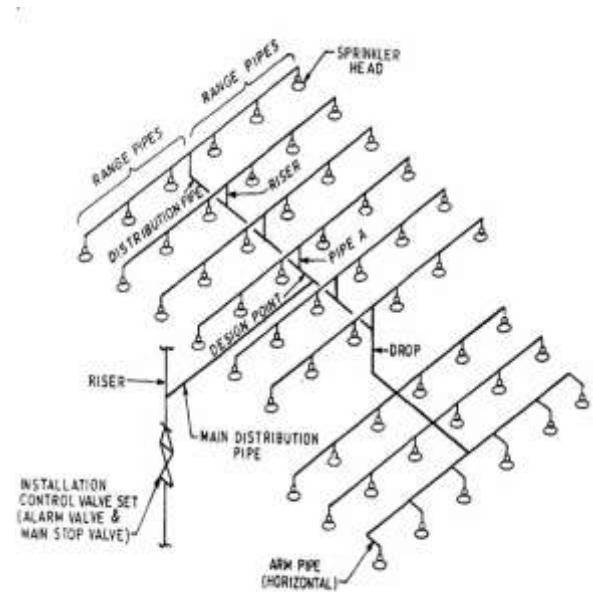


FIG. 1 MAIN ELEMENTS OF A SPRINKLER INSTALLATION

A sprinkler has two functions to perform. It must first detect a fire, and must then provide an adequate distribution of water to control or extinguish it. Each function is performed separately and one is independent of the other except insofar as early detection makes extinction easier because the fire has not grown large. The classic use of the sprinkler is in the hot gas layer which forms beneath the ceiling of an enclosure in which a fire is developing. The sprinklers operate at pre-determined temperatures to discharge water over the affected part of the area below, the flow of water through the alarm valve initiating a fire alarm. The operating temperature is generally selected to suit ambient temperature conditions. Only sprinklers in the vicinity of the fire, i.e., those which become sufficiently heated, operate. It should not be assumed that the provision of sprinkler system entirely obviates the need for other means of fighting fires and it is important to consider the fire precautions in the premises as a whole.

Types of Automatic Sprinkler Systems

- Wet Pipe Systems
- Dry Pipe Systems
- Preaction Systems
 - Non-Interlock Preaction System
 - Single Interlock Preaction System
 - Double Interlock Preaction System
- Deluge Systems

Standard automatic sprinkler system design Purpose and Objectives:

Automatic sprinkler systems are designed to detect and suppress fires at an early stage, protecting lives and minimizing property damage. The systems aim to deliver

adequate water flow and pressure to extinguish or control fire in a specific area.

Design Principles: Hydraulic Calculations: Fundamental to ensure adequate water distribution. Includes determining pipe sizes, flow rates, and pressure requirements based on the system's layout and the fire hazard classification. **Design Criteria:** Depends on the occupancy type (e.g., light, ordinary, or high hazard), ceiling height, and potential fire spread.

Sprinkler Layout: Adherence to specific standards such as NFPA 13, IS 15105 and others. Sprinklers are spaced to provide uniform coverage, taking into account the maximum allowable distances between sprinklers and the walls. **Hydraulic Design Methods:** Pipe Schedule Method: Suitable for simpler systems and older standards but less efficient for larger or complex installations.

Hydraulically Calculated Systems: Modern systems using software tools to optimize pipe sizing and water flow.

Sprinkler system fails due to :

- Inadequate water supply in the system
- Lack of proper design
- Less number of sprinkles in the protected area,
- lower size of sprinkler nozzle (flow rate, discharge pressure, water distribution pattern.)
- underestimation of protected hazard,
- higher rating of sprinkler heads
- improper maintenance

Key Components of Automatic Sprinkler Systems

• **Sprinkler Heads:** These are the outlets where water is discharged. Each sprinkler head has a heat-sensitive element. Sprinkler heads are classified as follows;

Based on Activation Mechanism:

- Fusible Link Sprinklers:
- Glass Bulb Sprinklers:
- Chemical Pellet Sprinklers:

Based on Water Distribution Pattern:

- Pendant Sprinklers:
- Upright Sprinklers:
- Sidewall Sprinklers:
- Concealed Sprinklers:

Temperature Rating and Color coding

(Clause 15.4)

Temperature Rating °C	Colour of Bulb Liquid
(1)	(2)
57	Orange
68	Red
79	Yellow
93	Green
141	Blue
182	Mauve
204/260	Black

Table 1 Color coding.

Sprinkler Designing for car parking basement area

According to IS 15105, automatic sprinkler systems for buildings are designed by classifying the occupancy into Light, Ordinary, High or Storage hazard categories, and the layout must satisfy several key requirements to ensure effective fire protection. Sprinklers are required to be spaced at least 1.8 m center-to-center so that their discharge patterns do not interfere with each other. The maximum center-to-center spacing is determined by the hazard class and layout and is further limited by a maximum floor-area coverage per sprinkler, which for ordinary (moderate) hazard occupancies is typically around 12 m² under ideal conditions. In addition, the distance from any wall or boundary to the nearest sprinkler must not exceed half of the spacing between adjacent sprinklers in both the direction of the range pipe and at right angles to it. Structural members such as beams, trusses or columns that might obstruct the water spray require careful consideration, and additional sprinklers or adjusted placement may be necessary in narrow bays or beneath obstructions to maintain complete coverage. Where special sprinkler types such as extended-coverage, large-drop or ESFR (early suppression fast response) heads are used, the standard provides separate tables specifying their maximum permissible spacing and coverage. Finally, sprinkler deflectors must be positioned between 25 mm and 150 mm

below the ceiling or roof deck (unless otherwise specified for the particular type of sprinkler) to ensure proper spray pattern development and uniform water distribution throughout the protected area.

Artificial neural network

What is Artificial Neural Network?

Artificial Neural Networks are relatively crude electronic models based on the neural structure of the brain. The brain basically learns from experience. It is natural proof that some problems that are beyond the scope of current computers are indeed solvable by small energy efficient packages. This brain modeling also promises a less technical way to develop machine solutions. This new approach to computing also

provides a more graceful degradation during system overload than its more traditional counterparts. These biologically inspired methods of computing are thought to be the next major advancement in the computing industry. Even simple animal brains are capable of functions that are currently impossible for computers. Computers do rote things well, like keeping ledgers or performing complex math. But computers have trouble recognizing even simple patterns much less generalizing those patterns of the past into actions of the future. Now, advances in biological research promise an initial understanding of the natural thinking mechanism. This research shows that brains store information as patterns. Some of these patterns are very complicated and allow us the ability to recognize individual faces from many different angles. This process of storing information as patterns, utilizing those patterns, and then solving problems encompasses a new field in computing. This field, as mentioned before, does not utilize traditional programming but involves the creation of massively parallel networks and the training of those networks to solve specific problems. This field also utilizes words very different from traditional computing, words like behave, react, self-organize, learn, generalize, and forget. Whenever we talk about a neural network, we should more popularly say —Artificial Neural Network (ANN)l, ANN are computers whose architecture is modelled after the brain. They typically consist of hundreds of simple processing units which are wired together in a complex communication network.

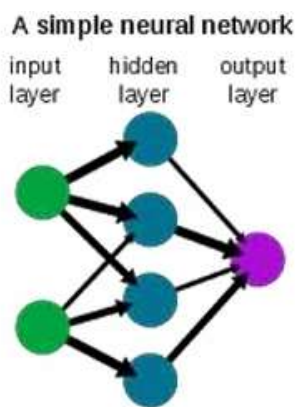


Fig 2 simple neural network

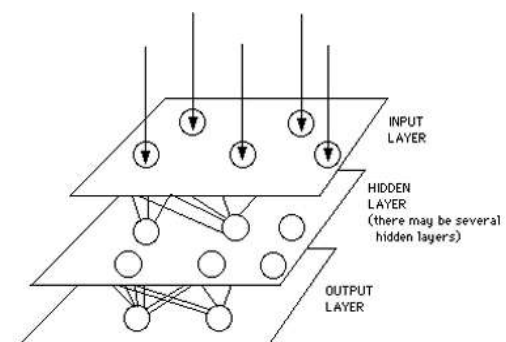
Each unit or node is a simplified model of real neuron which sends off a new signal or fires if it receives a sufficiently strong Input signal from the other nodes to which it is connected. Traditionally neural network was used to refer as network or circuit of biological neurons, but modern usage of the term often refers to ANN. ANN is mathematical model or computational model, an information processing paradigm i.e. inspired by the way biological nervous system, such as brain information system. ANN is made up of interconnecting artificial neurons which are programmed like to mimic the properties of m biological neurons. These neurons working in unison to solve specific problems. ANN is configured for solving artificial intelligence problems without creating a

model of real biological system. ANN is used for speech recognition, image analysis, adaptive control etc. These applications are done through a learning process, like learning in biological system, which involves the adjustment between neurons through synaptic connection. Same happen in the ANN.

Converted to a high-level language program and then into machine code that the computer can understand. These machines are totally predictable; if anything goes wrong is due to a software or hardware fault. Neural networks and conventional algorithmic computers are not in competition but complement each other. There are tasks are more suited to an algorithmic approach like arithmetic operations and tasks that are more suited to neural networks. Even more, a large number of tasks, require systems that use a combination of the two approaches (normally a conventional computer is used to supervise the neural network) in order to perform at maximum efficiency.

The study of the human brain is thousands of years old. With the advent of modern electronics, it was only natural to try to harness this thinking process. The first step toward artificial neural networks came in 1943 when Warren McCulloch, a neurophysiologist, and a young mathematician, Walter Pitts, wrote a paper on how neurons might work. They modeled a simple neural network with electrical circuits. Neural networks, with their remarkable ability to derive meaning from complicated or imprecise data, can be used to extract patterns and detect trends that are too complex to be noticed by either humans or other computer techniques. A trained neural network can be thought of as an "expert" in the category of information it has been given to analyses.

Other advantages include:



1. Adaptive learning: An ability to learn how to do tasks based on the data given for training or initial experience.
2. Self-Organization: An ANN can create its own organization or representation of the information it receives during learning time.
3. Real Time Operation: ANN computations may be carried out in parallel, and special hardware devices are being designed and manufactured which take advantage of this capability.

4. Fault Tolerance via Redundant Information Coding: Partial destruction of a network lead to the corresponding degradation of performance. However, some network capabilities may be retained even with major network damage.

Neural networks take a different approach to problem solving than that of conventional computers. Conventional computers use an algorithmic approach i.e. the computer follows a set of instructions in order to solve a problem. Unless the specific steps that the computer needs to follow are known the computer cannot solve the problem. That restricts the problem-solving capability of conventional computers to problems that we already understand and know how to solve. But computers would be so much more useful if they could do things that we don't exactly know how to do. Neural networks process information in a similar way the human brain does. The network is composed of a large number of highly interconnected processing elements (neurons) working in parallel to solve a specific problem. Neural networks learn by example. They cannot be programmed to perform a specific task. The examples must be selected carefully otherwise useful time is wasted or even worse the network might be functioning incorrectly.

Fig 3 Simple neural network diagram.

The model may generalize and forecast unseen data after learning from the initial inputs and their associations, as well as from unforeseen relationships inferred from unobserved data. The disadvantage is that because the network finds out how to solve the problem by itself, its operation can be unpredictable. On the other hand, conventional computers use a cognitive approach to problem solving; the way the problem is to solved must be known and stated in small unambiguous instructions. And the figure let us know about the artificial neural network how is that work as it coordinates with the input data to get trained and predict the result.[14]

ANN Applications in Automatic Fire Sprinkler

Artificial Neural Networks (ANNs) have emerged as powerful computational tools for solving complex problems in fire protection engineering, particularly in basement car parks where traditional prescriptive design approaches often fail to capture the highly nonlinear and dynamic nature of fire growth and sprinkler performance. One of the key advantages of ANN models is their ability to handle nonlinear input–output relationships, which are difficult to address using classical hydraulic equations or simplified fire hazard classifications. Unlike deterministic methods such as Hazen–Williams or Darcy–Weisbach, ANNs can capture the nonlinear interactions between variables such as fire load, ceiling height, ventilation rate, and sprinkler response [14].

Another significant advantage is the adaptive learning capability of ANN models. Through training on experimental or simulated fire datasets, ANNs continuously improve their

predictive accuracy. This adaptive feature is highly relevant in underground car parking scenarios where fire hazards are uncertain and vary depending on vehicle types, materials, and geometry. For instance, ANN-based models have been shown to outperform linear regression and traditional empirical correlations in predicting heat release rate, temperature evolution, and sprinkler activation times [15].

ANNs are also promising in the prediction of fire growth dynamics. Vehicle fires in basement structures are characterized by rapid smoke spread, fluctuating heat release rates, and interactions with ventilation. By learning from fire growth patterns, ANN models can provide early predictions of critical fire parameters such as smoke layer height, visibility loss, and gas concentrations. This allows for real-time decision support in activating sprinklers and optimizing mechanical exhaust systems [5].

In addition, ANN approaches can be applied to hydraulic demand optimization of sprinkler networks. Traditional sprinkler design codes, such as NFPA 13 or NBC 2016, prescribe fixed density–area methods, which often lead to conservative or inefficient system designs in complex layouts. ANN-based optimization allows the modeling of sprinkler hydraulics under varying demand scenarios, accounting for pipe network geometry, pressure losses, and dynamic fire loads. Studies have demonstrated that ANN-driven optimization can minimize water demand while ensuring adequate coverage and system reliability, thereby reducing both cost and risk [16].

Overall, the integration of ANN into sprinkler system design for basement car parks provides a data-driven, adaptive, and efficient approach that surpasses traditional prescriptive methods. Its advantages—nonlinear modeling, adaptive learning, prediction of fire growth, and hydraulic optimization—make it a transformative tool for modern fire safety engineering.

AI gave fewer sprinklers in most of the cases, as shown in Fig. 10. It suggests that AI provides more cost-effective solutions with a reasonable number of sprinklers, which allows for opportunities of design optimization in practices. The reason is that, while the code specifies the maximum spacing requirement for sprinklers, the most cost-effective solution is that all the sprinklers are arranged with that value. However, it is a common practice for engineers to use a more conservative spacing to distribute sprinklers, rather than following the maximum value.

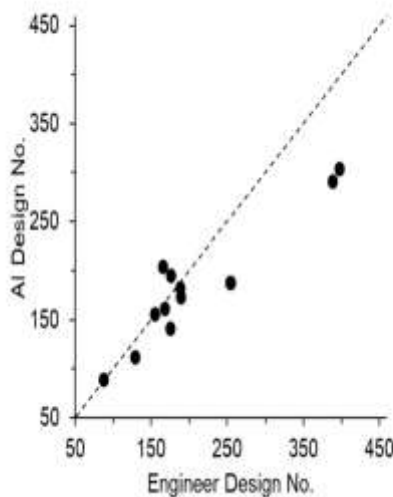


Fig. 4. Comparisons of number of designed sprinkler heads by engineer and AI for testing cases.

The reason is that the sprinkler layout design is very sensitive to the architectural plan and, meanwhile, design changes are quite common during the whole design period. If the sprinklers are maximum-spacing designed at the initial stage, they may face very frequent modifications in the following stages, which will cost them a lot. Therefore, it has become a commonly accepted practice that sprinklers are conservatively designed with tolerance for future design modification.[1]

Machine learning especially feedforward artificial neural networks (ANNs) and newer tabular neural architectures are increasingly applied to fire-safety tasks where complex, nonlinear relationships exist between inputs (geometry, ventilation, combustible load, detection times) and outputs (flow, pressure, heat release rate (HRR), sprinkler activation). Recent studies show ANNs can rapidly approximate relationships learned from experiments, tests, or CFD simulations, making them attractive for fast prediction, optimization, and real-time control in car-park environments.

Smart sprinkler activation based on ANN predictions

- **Concept:** Use ANN predictions of near-term HRR, temperature rise, or required discharge to trigger staged or localized sprinkler activation rather than global system actuation. This can reduce water damage and tailor protection to real hazard severity (e.g., isolating a single car fire). [17]
- **IoT and sensors:** When integrated with IoT sensors (temperature, optical, gas), ANN inference can run on edge hardware to deliver near-real-time activation decisions. However, reliability, fail-safe design, and regulatory acceptance remain important barriers.[18]

ANN for optimal sprinkler head placement and zoning

- **Approach:** ANNs (sometimes combined with optimization heuristics such as genetic algorithms or MILP) are used to map from floorplan/geometry and hazard distribution to optimal head locations, spacing, and zoning that maximize coverage or minimize required water while satisfying design constraints. Recent work merges ANN surrogates with optimization loops to speed search.[19]
- **Why useful in parking garages:** Parking layouts have irregular obstructions (columns, ramps, parked vehicles) and highly variable hazard sources (EV vs ICE vehicles). Data-driven placement can adapt to such complexity better than purely prescriptive spacing rules.[20]

ANN integration with fire load and Heat Release Rate (HRR) data

- **Predicting HRR from observable features:** ANNs (and other ML models) have been developed to reconstruct or predict time-varying HRR from measurable signals or material/enclosure properties. Such HRR predictions can be fed into sprinkler control logic (e.g., trigger thresholds, staged activation).[21]
- **Vehicle fire datasets & inputs:** For parking scenarios, useful ANN inputs include vehicle count/type (EV/ICE), ventilation rates, ceiling height, compartment geometry, and sensor time-series (temperature, optical/IR, smoke). Models trained on vehicle-fire experiments or high-fidelity simulations can estimate peak HRR timing and intensity for downstream control decisions.[22]

Artificial Neural Networks (ANNs) are increasingly being recognized as transformative tools in the domain of automatic fire sprinkler design, particularly for basement car parks where conventional prescriptive codes often fail to capture the complexity of fire dynamics. Unlike classical deterministic approaches such as Hazen–Williams or Darcy–Weisbach, which assume linear relationships and fixed density–area methods, ANNs can effectively model the nonlinear interactions between key variables including fire load, ventilation rate, ceiling height, and sprinkler response. This makes them especially relevant in underground parking structures, where fire scenarios vary significantly depending on vehicle type, material composition, and geometry. Recent studies demonstrate that ANN-driven optimization can reduce the number of required sprinklers compared with engineer-designed layouts, primarily because AI algorithms tend to adopt maximum code-allowed spacing rather than the more conservative arrangements commonly used in practice. Such

outcomes highlight the potential of ANN to deliver cost-effective and efficient designs while still adhering to safety standards. Moreover, the adaptive learning capability of ANN models enables them to improve predictive accuracy with additional fire-test or simulation data, making them robust against the uncertainties associated with emerging hazards such as electric vehicle fires. Beyond hydraulic demand estimation, ANN applications extend to predicting heat release rates, smoke spread, and sprinkler activation times, providing an advanced understanding of fire growth dynamics that traditional models cannot capture. Integration with IoT sensor networks further enhances their utility, allowing near real-time analysis of temperature, smoke, or gas concentrations to support smart sprinkler activation strategies. Instead of global system discharge, ANN-based predictions can trigger localized or staged activation, minimize water damage while tailor the response to actual hazard severity. Additionally, when combined with optimization techniques such as genetic algorithms or mixed-integer linear programming, ANN surrogates can rapidly identify optimal sprinkler head placement and zoning in irregular parking geometries with obstructions such as columns and ramps. These developments indicate that ANN not only optimizes hydraulic and spatial design but also supports intelligent control and adaptability, thereby offering a comprehensive, data-driven approach to fire protection in basement car parks that goes beyond the limitations of conventional prescriptive standards.

Conclusion

From this review it is clear that artificial neural networks (ANNs) can bring a major shift in how sprinkler systems are designed for basement car parks. Traditional methods, which follow fixed rules and hazard categories, often struggle with the unpredictable and highly dynamic nature of fires in these confined spaces. ANNs, on the other hand, are able to learn from real fire data, experiments, and simulations, which makes them better at predicting how a fire will grow, how smoke will spread, and when sprinklers should activate.

The studies reviewed show that ANN-based designs can achieve the same level of safety as code-based methods but with fewer sprinkler heads, less water demand, and reduced design time. This means they are not only safer but also more cost-effective. When combined with modern sensor networks and smart building systems, ANNs also open the door to more intelligent fire control—for example, activating only the sprinklers needed in a specific zone rather than the whole system, which reduces water damage and makes the response more targeted.

In short, ANNs provide a flexible, data-driven alternative to rigid prescriptive codes and are especially useful in handling new challenges like electric vehicle fires in car parks. While more work is still needed to build standard datasets, gain regulatory approval, and test these systems in real-world

projects, the potential is clear: ANN-driven sprinkler design could become a key part of the next generation of fire protection in complex underground structures.

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