RESEARCH TECHNICAL REPORT

Evaluation of the Availability of the SMART Sprinkler System

FM Global

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Prepared by

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Disclaimer

Executive Summary

The Simultaneous Monitoring, Assessment, and Response Technology (SMART) has been designed to overcome the limitations of traditional wet sprinkler system when used under very high challenge conditions (e.g., suppression of roll paper fires in high storage configuration warehouses greater than 42 feet storage height). This report presents the results of a study conducted to (1) evaluate the availability of the SMART sprinkler protection system, and compare with that of a traditional wet sprinkler protection system; and (2) conduct a comparative cost-benefit analysis for the SMART sprinkler protection and the traditional wet sprinkler protection systems.

In this study, the same type of water supply (i.e., public supply and fire pump) has been considered for both the SMART sprinkler protection and the traditional wet sprinkler protection systems. For the availability and the cost-benefit analyses, both the wired and wireless configurations of the SMART sprinkler system were considered. The cost-benefit analysis has been conducted to evaluate the Present Value of Net Benefit (PVNB), which is the difference between the Present Value (PV) of benefits and the PV of costs. In this study, benefit is defined as risk-reduction ($Risk_{no\ protection} - Risk_{with\ protection}$) achieved from the use of a fire protection system, while costs include Inspection/Testing/Maintenance (ITM) and initial installation costs for the fire protection system. To evaluate risk for the cost-benefit analysis of both the SMART sprinkler protection and the traditional wet sprinkler protection systems, this study considered a representative warehouse (50,000 ft^2 floor area) with an approximate total 'property and outage' cost of \$17.7M and a fire frequency of 0.025/year. In this study, risk is defined as the product of 'probability of occurrence of an undesired event' and 'severity of consequences associated with the undesired event'.

The main findings/conclusions of this study are as follows:

1. Availability evaluation:
   - While the availability of the traditional wet sprinkler system is 0.97 over the lifetime of 30 years, the availabilities of the SMART sprinkler systems are approximately 0.86±0.01 and 0.83±0.01, respectively, for the wired and wireless configurations. The higher availability of the traditional wet sprinkler system is due to its lower complexity and fewer components when compared to the SMART sprinkler system.
   - Due to higher reliability of the wired connections, the unavailability of the wired SMART sprinkler system is approximately 20% lower than that of the wireless SMART sprinkler system.
   - The difference in the availabilities of the traditional wet sprinkler and the SMART sprinkler systems can be reduced by approximately 50% by increasing the ITM frequency of the SMART sprinklers from annual to semi-annual.
   - The smoke detector, control unit, solenoid valve, and fire pump (including water supply) are the critical components with regards to system availability for both the wired and wireless configurations of the SMART sprinkler system.

2. Cost-benefit analysis:
   The cost-benefit analysis has been performed with a limited objective of providing some comparative perspective into the costs and benefits associated with the SMART sprinkler protection and the traditional wet sprinkler protection systems.
   - For both the traditional wet sprinkler and the SMART sprinkler systems, the estimated lifetime risk-reductions are more than 90%.
   - The estimated lifetime ITM cost for the traditional wet sprinkler system is approximately 50% lower than those of the wired/wireless SMART sprinkler systems.
   - For the traditional wet sprinkler system installed in a low storage configuration warehouse (i.e., less than 42 feet storage height), the estimated lifetime PVNB is approximately two to three times higher than those for the wired/wireless SMART sprinkler systems installed in a high storage configuration warehouse.
   - For the SMART sprinkler system, the estimated lifetime PVNBs are comparable with annual and semi-annual ITMs.
   - The estimated lifetime PVNB for the wired SMART sprinkler system is approximately 30% higher than that for the wireless system.

The SMART sprinkler configuration used in this study is expected to change when implemented commercially (e.g., using an alternative to the solenoid valve or using a different activation mechanism or different sensors). Therefore, the values of the availability and the PVNB estimated in this study are only intended as general guidance and are expected to change according to actual system design and components.

Abstract

This report presents the results of a study conducted to (1) evaluate the availability of the wired/wireless SMART sprinkler protection systems (for warehouses with a storage height greater than 42 feet), and compare it with that of a traditional wet sprinkler protection system (for warehouses with a storage height less than 42 feet); and (2) conduct a comparative cost-benefit analysis for the SMART sprinkler protection and the traditional wet sprinkler protection systems. For the availability and the cost-benefit analyses, both the wired and wireless configurations of the SMART sprinkler system were considered. The cost-benefit analysis has been conducted to evaluate Present Value of Net Benefit (PVNB), which is the difference between the Present Value (PV) of benefits and the PV of costs. In this study, benefit is defined as risk-reduction achieved from the use of a fire protection system, while costs include Inspection/Testing/Maintenance (ITM) and initial installation costs for the fire protection system.

While the availability of the traditional wet sprinkler system is 0.97 over the lifetime of 30 years, the availabilities of the SMART sprinkler systems are approximately 0.86±0.01 and 0.83±0.01, respectively, for the wired and wireless configurations. The difference in the availabilities of the traditional wet sprinkler and the SMART sprinkler systems can be reduced by approximately 50% by increasing the ITM frequency of the SMART sprinklers from annual to semi-annual.

For both the traditional wet sprinkler and the SMART sprinkler systems, the estimated lifetime risk-reductions are more than 90%. The estimated lifetime ITM cost for the traditional wet sprinkler system is approximately 50% lower than those of the wired/wireless SMART sprinkler systems. For the traditional wet sprinkler system installed in a low storage configuration warehouse, the estimated lifetime PVNB is approximately two to three times higher than those for the wired/wireless SMART sprinkler systems installed in a high storage configuration warehouse. The estimated lifetime PVNB for the wired SMART sprinkler system is approximately 30% higher than for the wireless system.

Acknowledgements

The author would like to thank Yibing Xin, Christopher Wieczorek, and Sergey Dorofeev for providing valuable inputs regarding the SMART sprinkler system design, installation, and cost; and for reviewing this report. The author would like to thank Kumar Bhimavarapu and Jens Alkemper for providing valuable feedback at all stages during this study, and for reviewing this report. The author would like to thank Francesco Tamanini and Louis Gritzo for supporting and encouraging this study, and for reviewing this report.

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1. Introduction

A major drawback of traditional wet sprinkler fire protection systems is significant response time, particularly in case of high ceiling clearance. To overcome this limitation of the traditional wet sprinkler system, an electronically controlled sprinkler activation system was first conceptualized and developed by Gefest Enterprise Group[i] in collaboration with the Russian Research Institute for Fire Protection[ii], with support from St.-Petersburg State Polytechnic University[iii] [1] [2]. The developed system is intended to provide fire protection in commercial, industrial, and storage sites with ceiling clearances up to 65 feet.

FM Global Research has also designed a system called the Simultaneous Monitoring, Assessment, and Response Technology (SMART) for suppression of fires in challenging storage configurations, such as high roll paper storage warehouses (i.e., greater than 42 feet storage height) [3] [4].

The objectives of this study are:

1. Evaluate the availability of the SMART sprinkler fire protection system, and compare it with that of a traditional wet sprinkler fire protection system.

   The objective of such a comparison is to evaluate whether SMART sprinkler systems would provide an availability similar to the availability of a traditional wet sprinkler system that is considered a benchmark in the fire protection industry.

2. Perform a comparative cost-benefit analysis for the SMART sprinkler protection and the traditional wet sprinkler protection systems.

   The objective of the cost-benefit analysis is limited to providing some comparative perspective into the costs and benefits associated with the SMART sprinkler protection and the traditional wet sprinkler protection systems.

The organization of this report is as follows. The definition of the SMART sprinkler system is provided in Chapter 2, which includes a description of the system and its operation, definition of failure of the system, and the postulates used in this study to perform the availability and the cost-benefit analyses. Chapter 3 provides results from a Failure Mode and Effects Analysis (FMEA) of the SMART sprinkler system. Chapter 4 provides the availability models for the SMART sprinkler system for both wireless and wired configurations. Chapter 5 provides results from the availability analysis (i.e., estimated availability values and the lifetime ITM costs for the SMART sprinkler system and the traditional wet sprinkler system). Chapter 6 provides results from risk estimations for the traditional wet sprinkler and the SMART sprinkler protection systems. Chapter 7 provides results from a comparative cost-benefit analysis for the SMART sprinkler protection and the traditional wet sprinkler protection systems. Finally, the conclusions are provided in Chapter 8.

[i] Gefest Enterprise Group, St.-Petersburg, Russia

[ii] Russian Research Institute for Fire Protection, VNIIPO, Balashikha, Russia

[iii] St.-Petersburg State Polytechnic University, St.-Petersburg, Russia

2. Definition of SMART Sprinkler System

This chapter describes the SMART sprinkler system and its operation requirements, definition of failure of the system, and postulates used in this study to perform the availability and the cost-benefit analyses.

2.1 Schematic of the System

Figures 2-1 and 2-2 show schematics of the proof-of-concept design of the SMART sprinkler for wireless and wired configurations, respectively. In case of wired configuration, the sensors communicate directly with the Programmable Logic Controller (PLC) using wires.

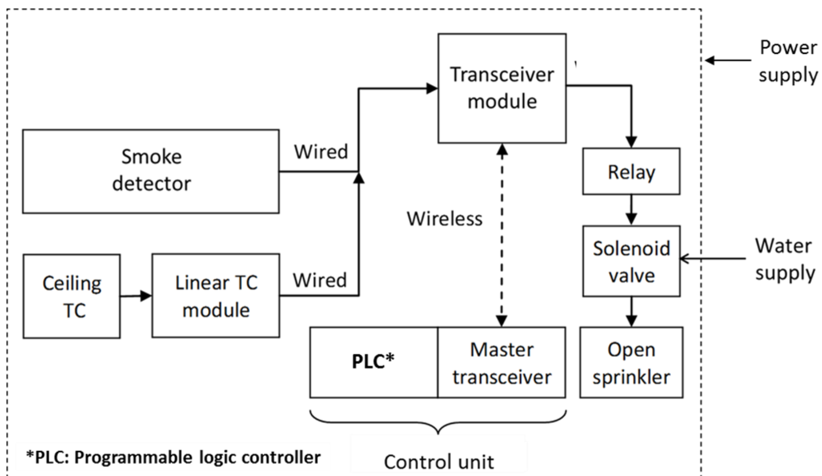

Figure 2-1: Schematic of the proof-of-concept design (wireless communication) of the SMART sprinkler (with system boundaries shown by the dashed line)

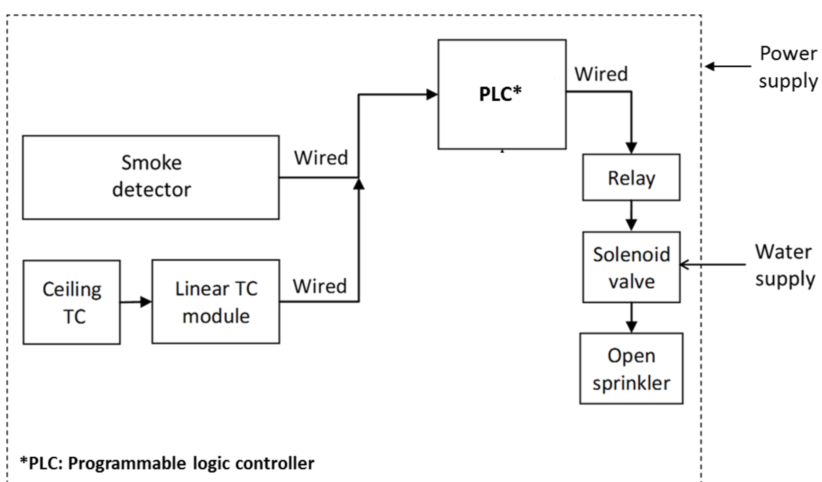

Figure 2-2: Schematic of the proof-of-concept design (wired communication) of the SMART sprinkler (with system boundaries shown by the dashed line)

2.2 Operation of the System

To overcome the limitations of the traditional wet sprinkler system for suppression of roll paper fires in high storage configuration warehouses, the SMART sprinkler system has been designed to activate and discharge water (at the desired flow rate) within a small acceptable window (a few seconds) after detection. Accordingly, within that acceptable window, the fire pump should be able to start and discharge water at the desired flow rate. If the fire pump fails to start/operate within that acceptable window then the SMART system will be ineffective (i.e., fail to suppress the fire). The following three sub-sections provide the operation requirements of the wireless and wired SMART sprinkler systems, as well as the activation criteria for the fire pump.

2.2.1 Wireless System

In the event of a fire, the smoke detectors and the thermocouples (TC) detect smoke and heat, respectively, and send signals to the transceiver modules, which transmit the signals wirelessly to the master transceiver located at the control unit. The PLC at the control unit analyzes the signals to determine (1) the need for system activation, and (2) the location of the fire and, if needed, communicates wirelessly (through the master transceiver) with the transceiver modules, which power the relays to energize and open the solenoid valves for discharge of water through open sprinklers.

2.2.2 Wired System

In the event of a fire, the smoke detectors and the TCs detect smoke and heat, respectively, and send signals to the PLC (control unit) using wires. The PLC analyzes the signals to determine (1) the need for system activation, and (2) the location of the fire and, if needed, powers the relays to energize and open the solenoid valves for discharge of water through open sprinklers.

2.2.3 Activation of Fire Pump for both Wireless and Wired SMART System

As per the revised configuration of the SMART sprinkler system, the fire pump starts based on a signal from either one of the sensors (and processing of data by the PLC), unlike the activation of the solenoid valve of the SMART sprinkler system that requires signals from both sensors meeting a defined threshold.

2.3 Definition of Failure of the System

A failure of the SMART sprinkler system is defined as no/inadequate discharge of water. Inadequate discharge refers to the case when water is discharged (1) from the incorrect sprinkler with respect to the fire location, or (2) at an inadequate flow rate (this includes the inability of the fire pump to reach the desired flow rate within the allowable time frame as applicable to the SMART sprinkler system).

2.4 Study Postulates

1. Availability evaluation:
    a. For the purposes of performing the availability/risk analysis, it is assumed that the proof-of-concept design is functional and effective with regards to the hazard being protected.

b. The components of the SMART sprinkler system have been selected based on the intended application conditions. For example, the temperature ratings of the components (e.g., the transceiver) should be adequate to meet the intended temperature conditions of a roll paper fire.

c. The proof-of-concept design uses a laptop (with an installed algorithm/software) for processing of the data from the smoke detectors and the TCs, and for controlling the activation of the SMART sprinkler system. For the evaluation of the availability of the SMART sprinkler system, the laptop (along with the algorithm/software) is considered as a typical PLC (similar to commercial systems).The algorithm/software (installed in the PLC) is assumed to have been adequately tested to meet the intended design functionality and effectiveness.

d. The proof-of-concept design of the wireless SMART system uses a wire to connect the signal transceiver module with the relay. For the evaluation of the availability of the wireless SMART system, a signal transceiver and a relay installed on the same Printed Circuit Board (PCB) are considered.

e. This study considered a conservative case of a single electric motor driven fire pump. In such cases, the National Fire Protection Association (NFPA) requires the electric power supply to be reliable [5]. The electric power failure probability used in this study is of the order of 10^{-5}, which can be considered to be highly reliable. Therefore, a back-up generator for the fire pump has not been considered in this study.

f. It has been considered that the fire pump would be able to activate and provide the desired flow rate of water within the acceptable window (a few seconds as applicable to the SMART system), provided the sensors (i.e., smoke detector and TC) and the control unit of the SMART system perform as intended. This ability of the fire pump needs to be investigated through field testing.

g. A typical system lifetime of 30 years was considered for the traditional wet sprinkler and the SMART sprinkler protection systems.

2. Risk and cost-benefit analysis:

   a. The fire frequency (λ), i.e., fire occurrence per warehouse per unit time interval, has been adopted from [6] for a medium sized warehouse. The upper limit value of 0.025/year (instead of the average of 0.0215/year [6]) has been considered in order to estimate the ‘probability of fire’.

   b. For a typical medium sized warehouse (50,000 ft^2), the total ‘property and outage’ cost is considered to be approximately \$17.7M @ \$354/ft^2 [6]. The total cost also includes any cranes that may be used inside the warehouse. For comparison purposes, the same total ‘property and outage’ cost value was used for both high storage configuration (SMART sprinkler protection) and low storage configuration (traditional sprinkler protection) warehouses.

   c. For the SMART sprinkler protection, a typical warehouse requires 500 SMART sprinklers (in typical wet system configuration) on a 10 feet by 10 feet spacing. Furthermore, it requires:

      i. One control unit (i.e., ‘PLC + master transceiver’ for wireless; ‘PLC’ for wired) per warehouse.

   ii. One fire pump system per warehouse.

   iii. One back-up (UPS) power supply for SMART sprinklers per warehouse.

d. Similarly, for the traditional wet sprinkler protection, a typical warehouse requires 500 traditional sprinklers on a 10 feet by 10 feet spacing.

e. For the scenario of ‘no protection’ in a warehouse, a severity of loss of 50% of the total ‘property and outage’ cost (i.e., approximately $8.85M) was considered. Even without automatic ceiling sprinkler protection systems, a warehouse can be protected from total loss by other forms of protection systems (including fire trucks).

f. The scenario of ‘failed protection system’ is considered to be equivalent to that of ‘no protection’. Therefore, for the scenario of ‘failed protection system’ in a warehouse, a severity of loss of 50% of the total ‘property and outage’ cost (similar to the scenario of ‘no protection’) was considered along with the installation cost of the protection system (since the protection system can get damaged during the fire).

g. To estimate the expected severity of loss with adequate protection (i.e., the protection system works properly) in a warehouse, a fire damage area of 400 ft^2 is adopted. The expected severity of loss can then be estimated to be approximately $141,600 (400 ft^2 @ approximately $354/$ft^2$ [6]).

h. The estimated cost of installation of a traditional wet sprinkler system is approximately $280,000 per warehouse @ $5.5/$ft^2$ [6]. The cost also includes the purchasing costs of the components (including water supply) of the traditional wet sprinkler system. For the SMART sprinkler protection in a warehouse, the installation cost is assumed to be the sum of $280,000 and purchasing costs of the SMART sprinklers (traditional sprinklers will be provided along with the SMART sprinklers). No additional labor costs were considered for installation of the SMART sprinklers.

i. To calculate the Present Value (PV) of cost incurred in future years, a discount rate of 4.8% was used [7].

j. The SMART sprinkler protection system consists of the SMART sprinklers and all the components of the traditional wet sprinkler system. The unit costs of Inspection/Testing/Maintenance (ITM) for the SMART sprinklers has been considered separately from that for the components of the traditional wet sprinkler system. Each SMART sprinkler consists of two sensors, a relay, a transceiver (or wired connection for wired system), electrical wires, a solenoid valve, and an open sprinkler. Furthermore, 500 SMART sprinklers (in a warehouse) are expected to share a control unit and a back-up power supply. In comparison, a traditional wet sprinkler system in a warehouse consists of a fire pump sub-system (one fire pump, electrical motor, and controller), check valves, ball valves, piping, and automatic sprinklers. In a warehouse, there is a significantly higher number of components for a SMART sprinkler protection system when compared to that for a traditional wet sprinkler protection system.

k. The values considered in this study (for the risk estimation and the cost-benefit analysis) are expected to vary based on the final (commercial) design of the SMART sprinkler system as well as the location/facility where the SMART sprinklers are expected to be installed.

3. Failure Mode and Effect Analysis (FMEA)

The FMEA is conducted to identify the credible failure modes of the components, the causes of failures, and the effects of failures on the SMART sprinklers. This analysis is necessary to build the availability model for the SMART sprinkler system. Tables 3-1 and 3-2 provide the results from the FMEA of the SMART sprinklers.

Table 3-1: FMEA of the SMART Sprinklers

Components	Functions	Failure Modes	Potential effects of failure on the system	Probable causes of failure
Smoke detector	Sense smoke; sound alarm; and send signal to transceiver module	No/erroneous signal to transceiver module	No/inadequate discharge through sprinklers; delayed activation of fire pump	Wear, corrosion, detector opening plugged/blocked, open circuit in sensing element
Thermocouple (TC) module	Measure temperature (heat); filter noise; send signal to transceiver module	No/erroneous signal to transceiver module	No/erroneous signal to transceiver module, hence no/inadequate discharge through sprinklers; delayed activation of fire pump	Corrosion, loose connection, open circuit in sensing element
Signal transceiver module	Communicate wirelessly (send and receive signals) with the master transceiver module, and energize the relay when required	Fail to act (i.e., communicate with master transceiver, and/or energize the relay when required)	Relay doesn't function, hence no discharge through sprinklers	Loss of antenna communication, corrosion, overstress, aging failures such as electromigration, diffusion, loss of power
Wireless communication	Provides connection between transceiver modules	Communication failure between signal and master transceivers	SMART sprinkler system failure to operate (if failure occurs prior to activation and not corrected)	External interference, e.g., radio frequency
Programmable logic controller (PLC)	Fire event assessment and location determination	Fail to accurately infer severity and location of fire event for sprinkler activation	No/inadequate discharge through sprinklers	Improper programming, corrosion, inadequate signal input, aging failures of processors

Table 3-2: FMEA of the SMART Sprinklers (continued)

Components	Functions	Failure Modes	Potential effects of failure on the system	Probable causes of failure
Master transceiver	Wireless communication with the transceiver module	Fail to act (i.e., communicate with signal transceiver module)	PLC fail to operate; no/inadequate discharge through sprinklers	Loss of power, loss of antenna communication, corrosion, overstress, aging failures such as electromigration, diffusion
Relay	When energized, provide a path for energizing the solenoid valve	Fail to provide a path for energizing the solenoid valve	Solenoid valve doesn't open, hence no discharge through sprinklers	No power received, open circuit or broken wire, wear, corrosion
Solenoid valve	Open to allow water to flow to sprinkler	Fail to open	No discharge through sprinklers	Wear, corrosion, blocked/plugged, inadequate power to energize
	Latch in open position once activated	Fail to latch	No discharge through sprinklers in the event of loss of power or failure of control unit	Corrosion, blocked/plugged, wear
Open sprinkler	Discharge water	Fail to discharge (e.g., at intended pattern or flow rate)	Fail to extinguish fire	Corrosion, blocked/plugged
Power supply (main, back-up)	Provide power supply for operation of SMART sprinkler system as well as fire pump; back-up supply provides power only to SMART system upon failure of main supply	Unavailable or fail to provide power	SMART sprinkler system as well as fire pump fail to operate, no discharge	Power generation and/or transmission failure; overstress, other random failures, corrosion
Electrical cable/wire	Convey electrical signals to components	Fail to convey	SMART sprinkler system fail to activate	Broken, worn out

4. **Availability Models for the SMART Sprinklers**

Availability is the probability that a system operates properly when needed. Availability of a system depends on the reliabilities of its components and the ITM parameters. Unavailability of a system can be caused by the following: (1) the system is in a failed condition or undergoing maintenance; and/or (2) the system fails to perform as intended when needed. For the wired/wireless SMART systems, this chapter provides the availability models, which include the unavailability trees, and the parameters for reliability distributions and ITM (including approximate costs per inspection/testing and maintenance).

For the traditional wet sprinkler system, the availability model has been adopted from past studies related to fire protection systems (e.g., [8] [9]), while the approximate ITM costs are provided in Appendix A. As discussed in Chapter 2, Section 2.4, the SMART sprinkler protection system consists of the SMART sprinklers and all the components of the traditional wet sprinkler system.

4.1 Unavailability Trees

The fault tree technique has been used to develop the unavailability trees for the wired/wireless SMART sprinklers. The unavailability trees have been developed using the results from the FMEAs (Chapter 3) to determine the logic leading to the unavailability of the wired/wireless SMART sprinklers.

For better presentation, the unavailability trees have been segregated into multiple figures (subtrees) with page number references (in each figure) providing connections between the different subtrees. Figures 4-1 to 4-8 provide the unavailability tree for the wireless SMART sprinkler, while Figures 4-9 to 4-14 provide the unavailability tree for the wired SMART sprinkler.

The solenoid valve failure mode ‘fail to latch’ is only relevant if, after activation, there is an interruption of signal from the relay to the solenoid valve either due to failure of the power supply or failure of the relay or wireless communication or other components upstream to the relay. Therefore, in the unavailability trees for the wireless and the wired SMART sprinklers, the intermediate event ‘solenoid valve fail to maintain open position upon activation’ has been modeled using an ‘AND’ gate with two events, i.e., ‘solenoid valve fail to latch’ and ‘relay fail to provide signal to solenoid valve’.

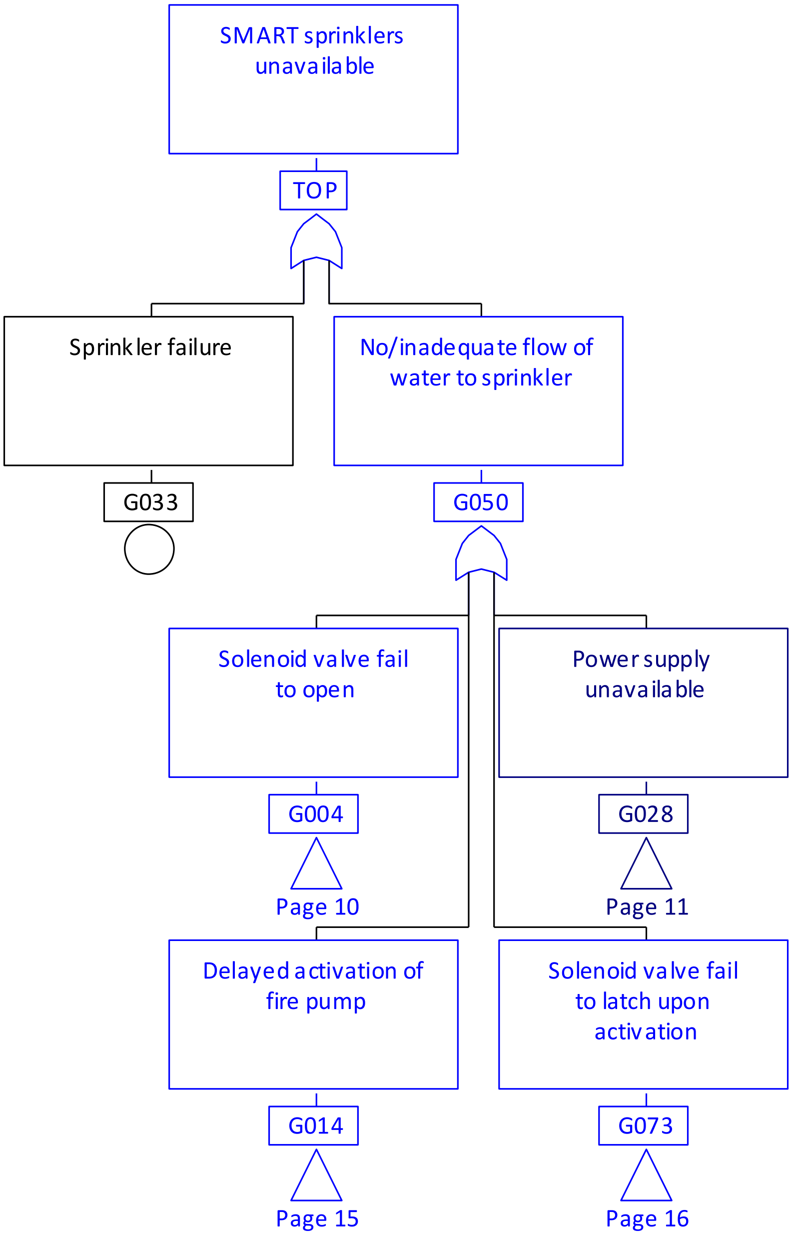

Figure 4-1: Unavailability tree for the wireless SMART sprinklers – Subtree I

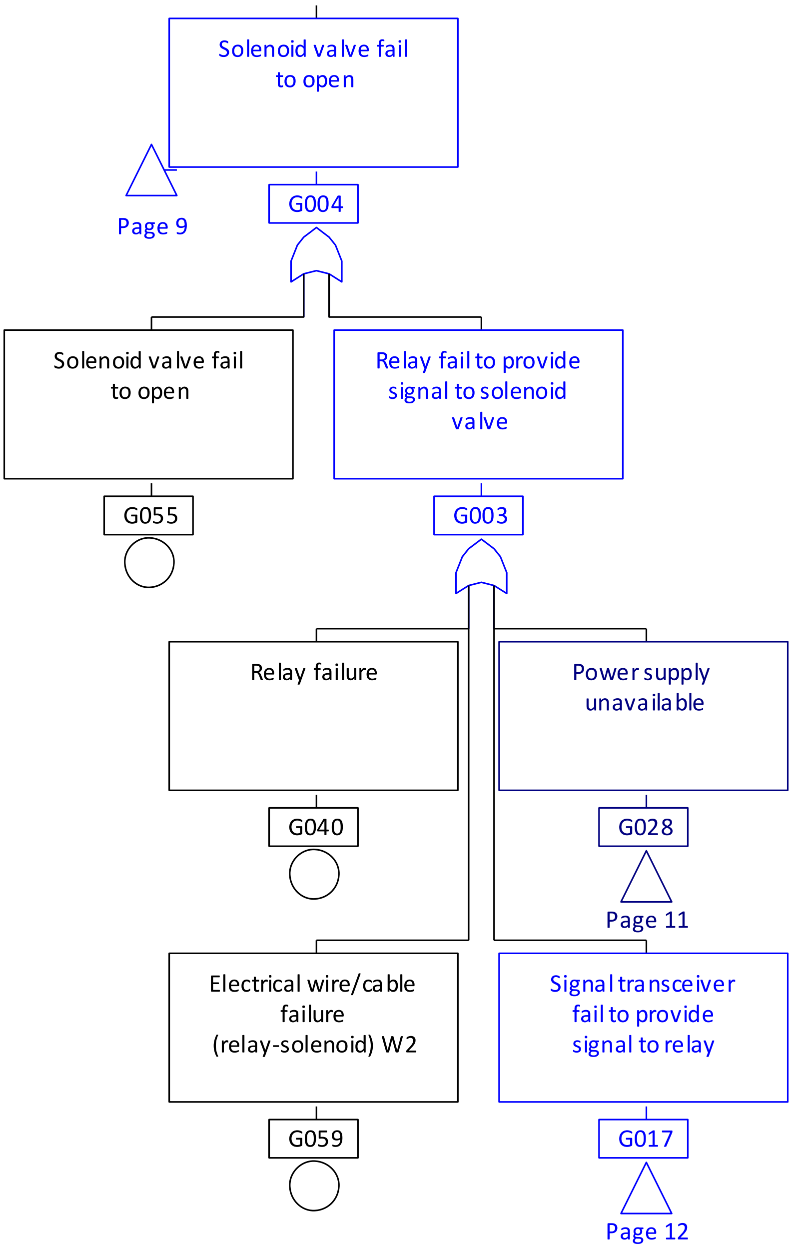

Figure 4-2: Unavailability tree for the wireless SMART sprinklers – Subtree II

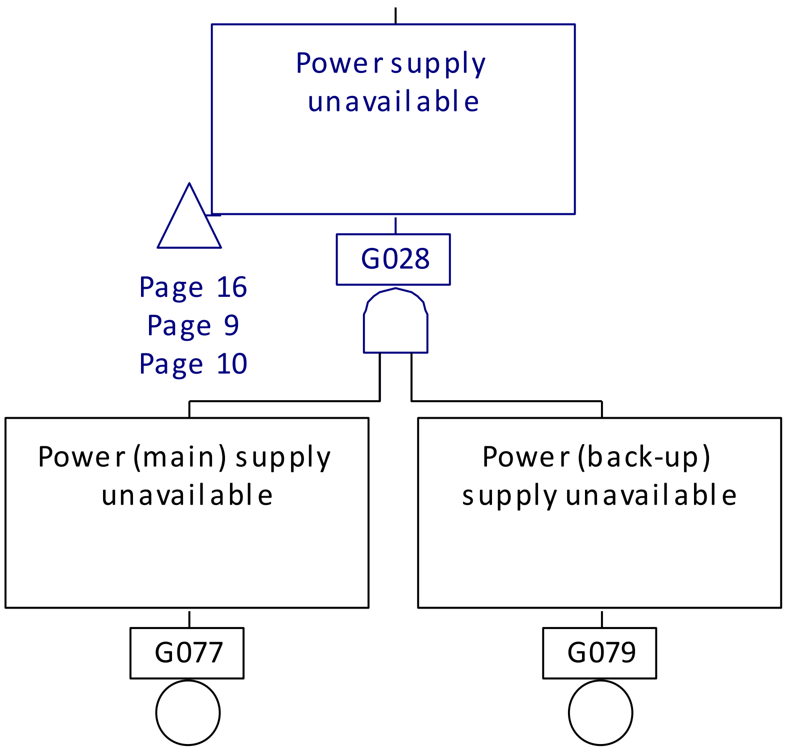

Figure 4-3: Unavailability tree for the wireless SMART sprinklers – Subtree III

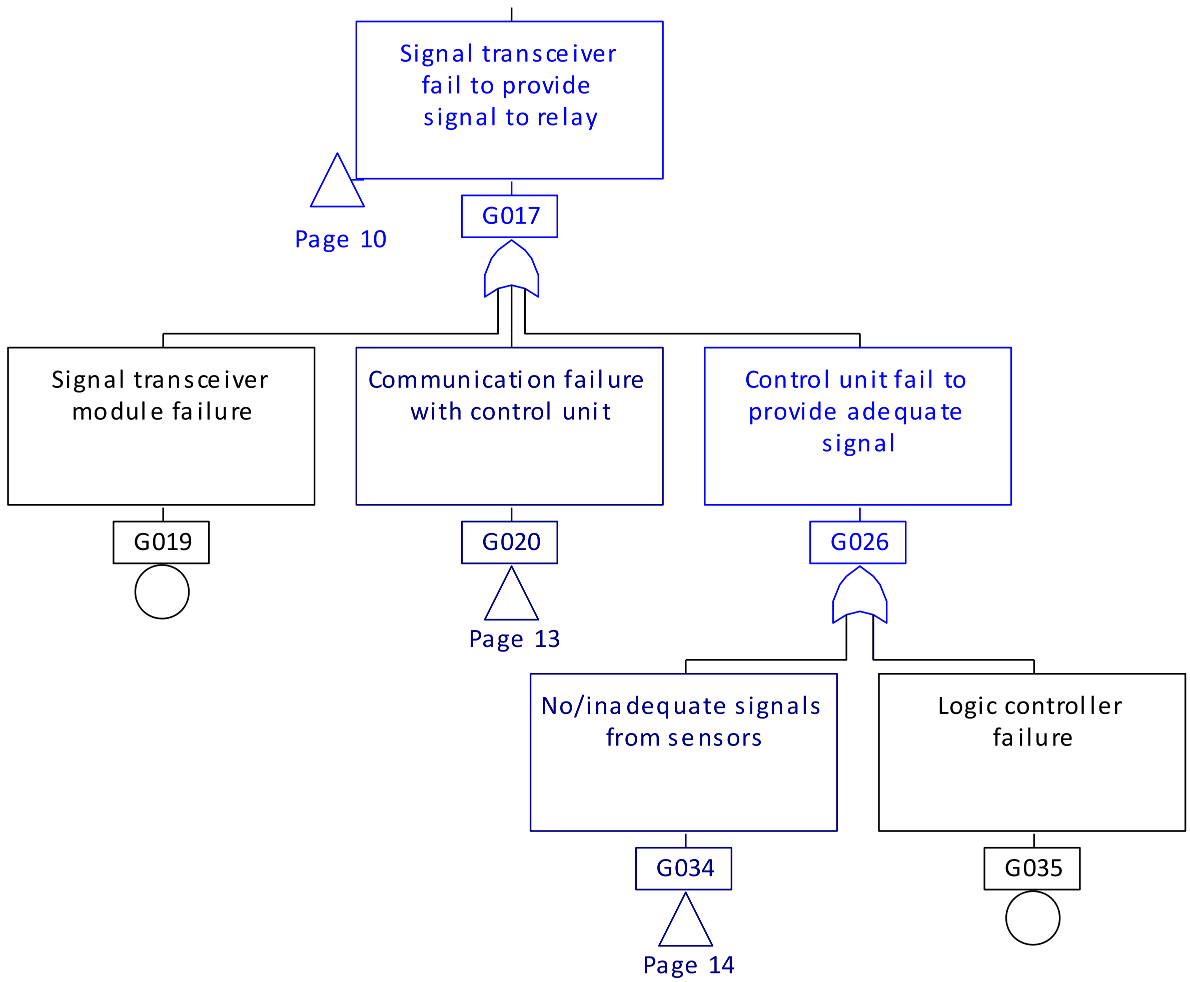

Figure 4-4: Unavailability tree for the wireless SMART sprinklers – Subtree IV

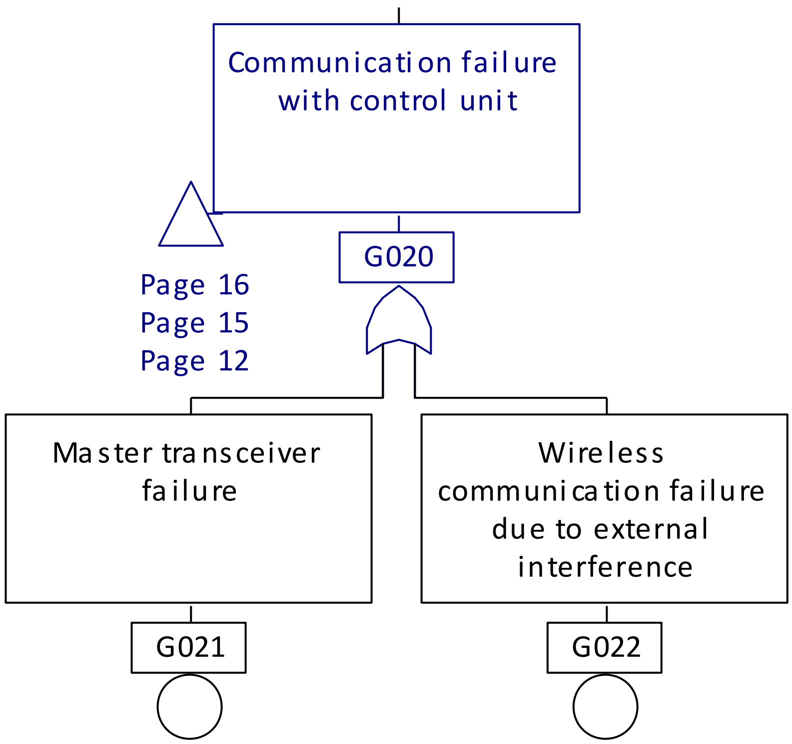

Figure 4-5: Unavailability tree for the wireless SMART sprinklers – Subtree V

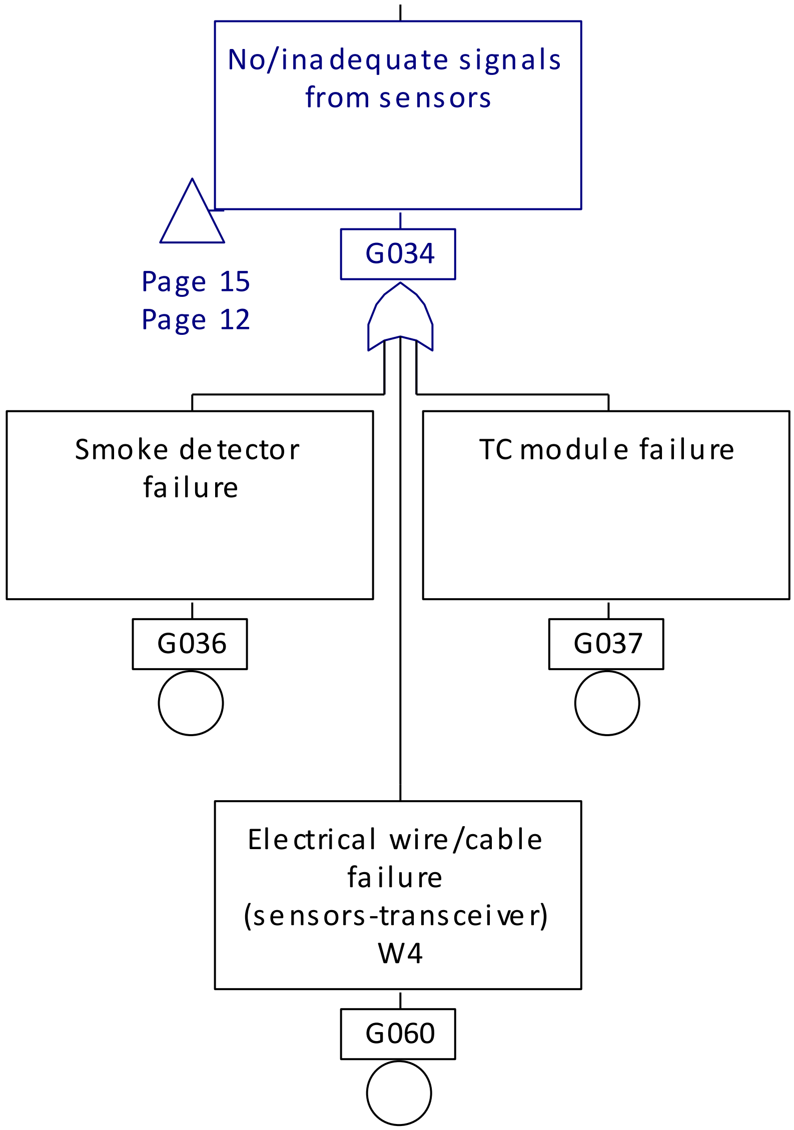

Figure 4-6: Unavailability tree for the wireless SMART sprinklers – Subtree VI

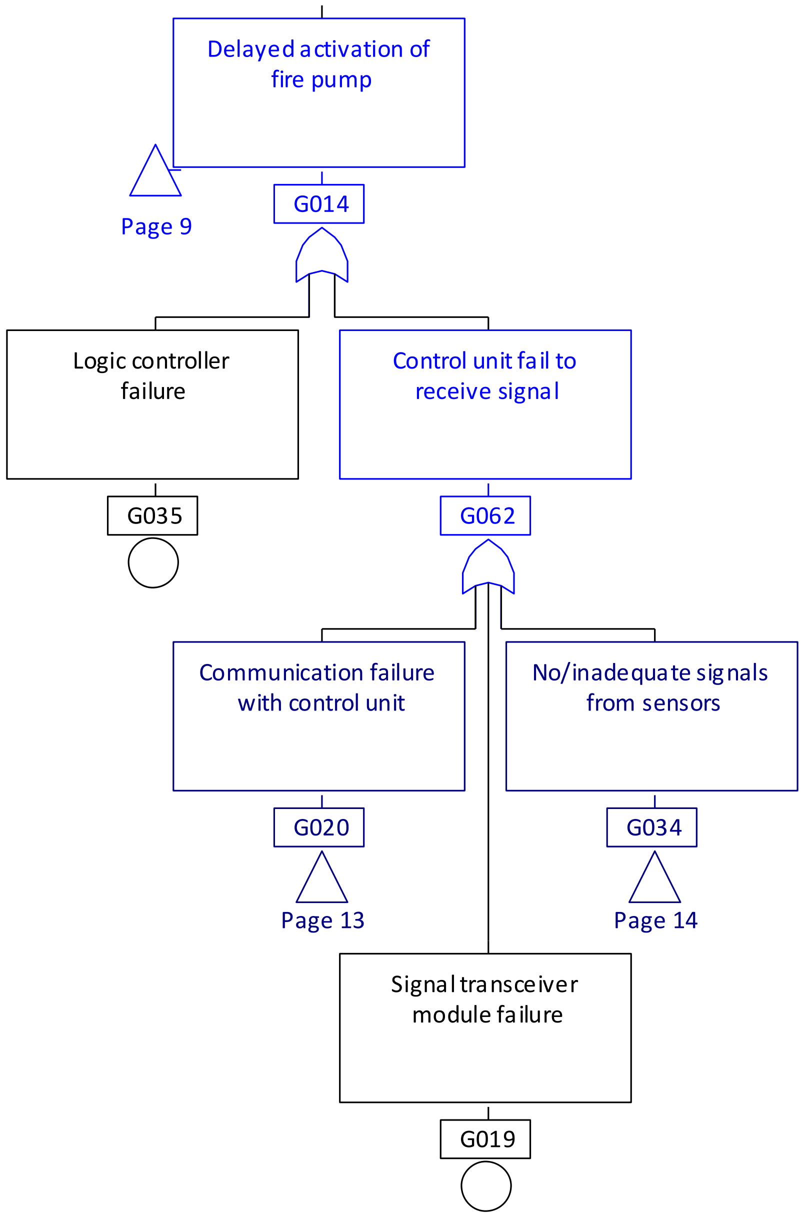

Figure 4-7: Unavailability tree for the wireless SMART sprinklers – Subtree VII

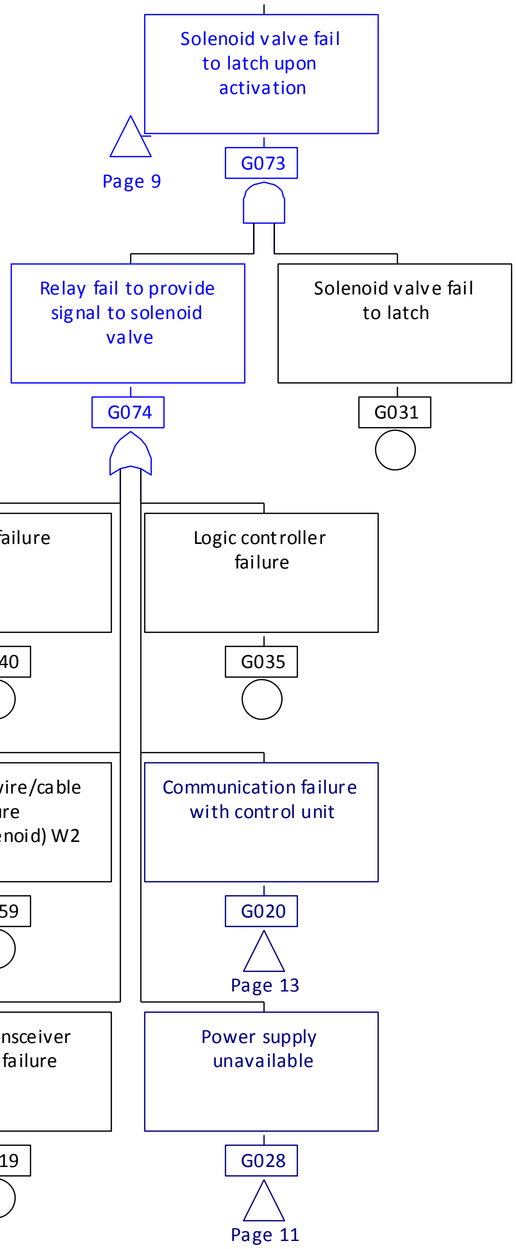

Figure 4-8: Unavailability tree for the wireless SMART sprinklers – Subtree VIII

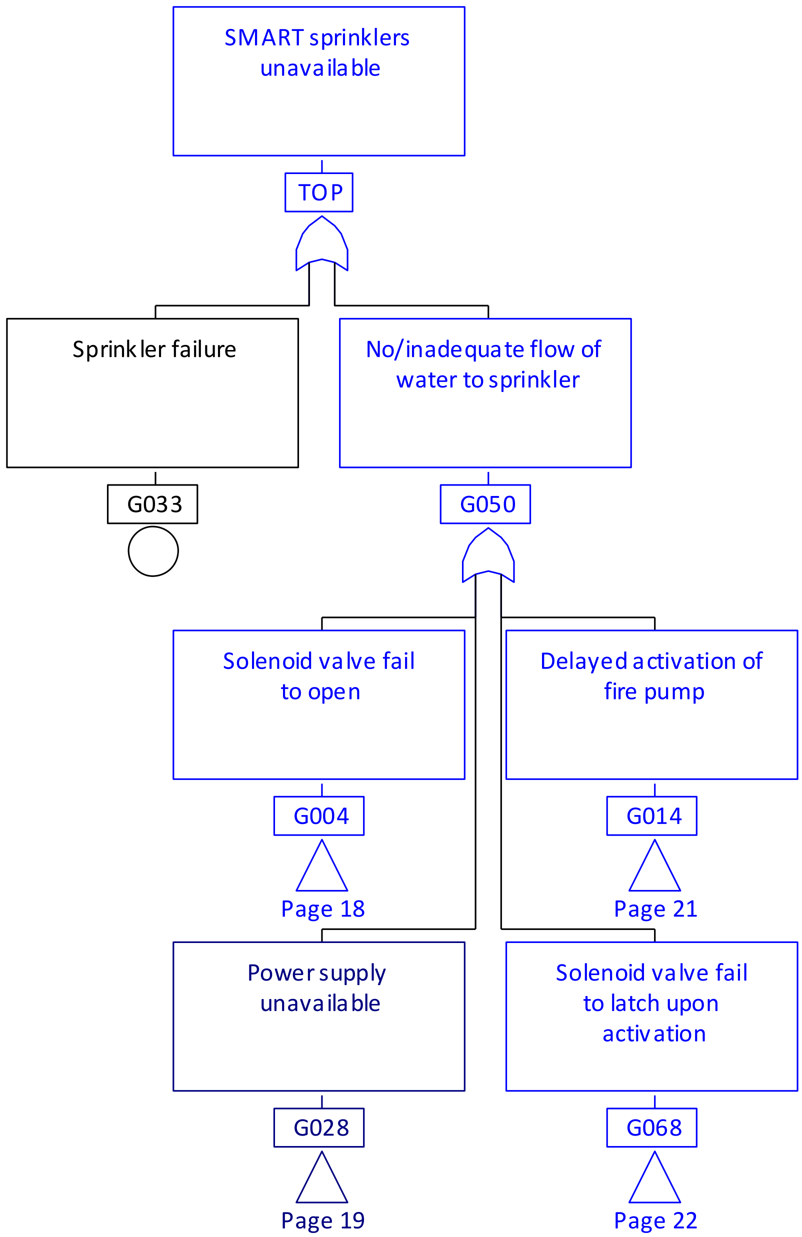

Figure 4-9: Unavailability tree for the wired SMART sprinklers – Subtree I

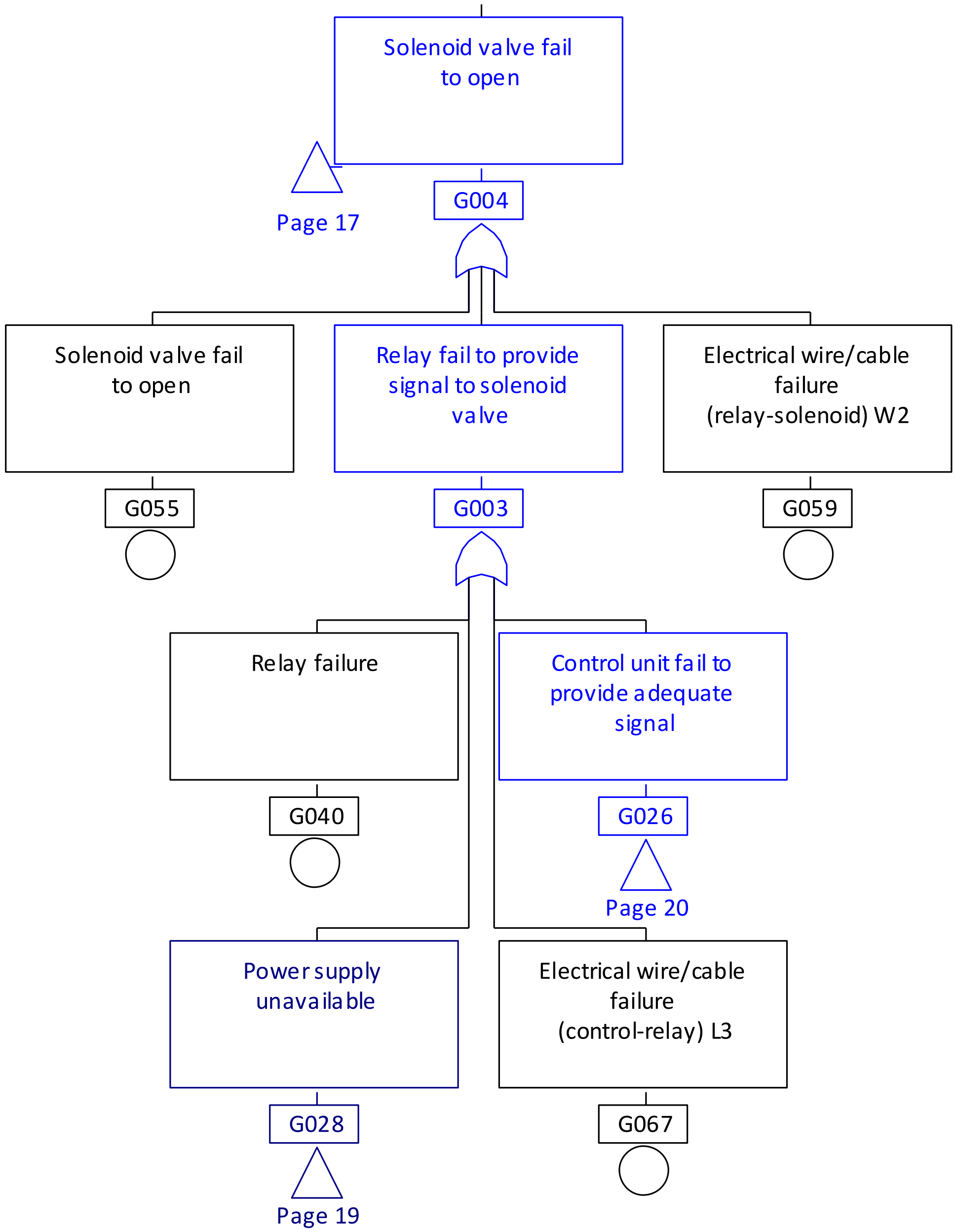

Figure 4-10: Unavailability tree for the wired SMART sprinklers – Subtree II

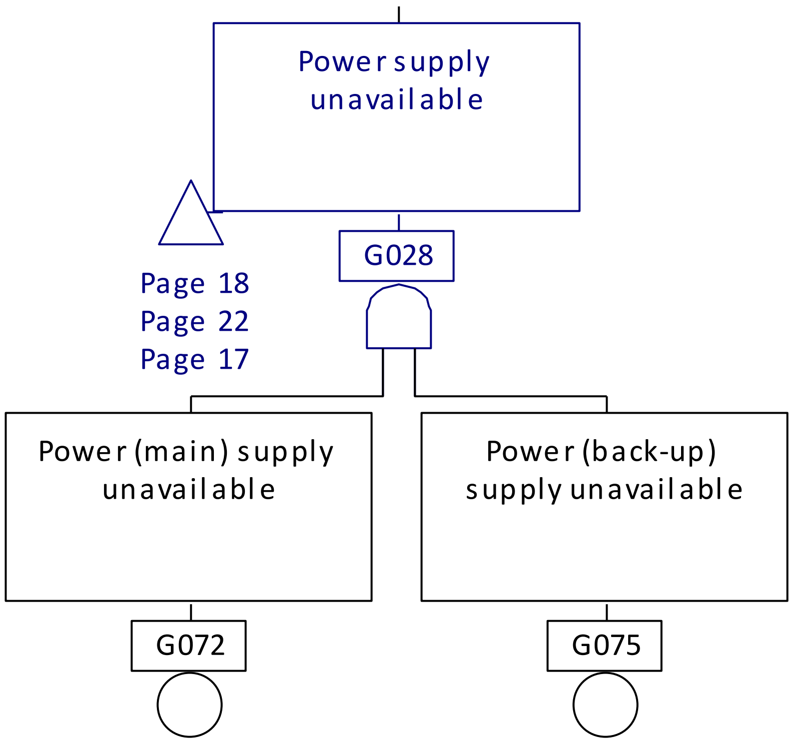

Figure 4-11: Unavailability tree for the wired SMART sprinklers – Subtree III

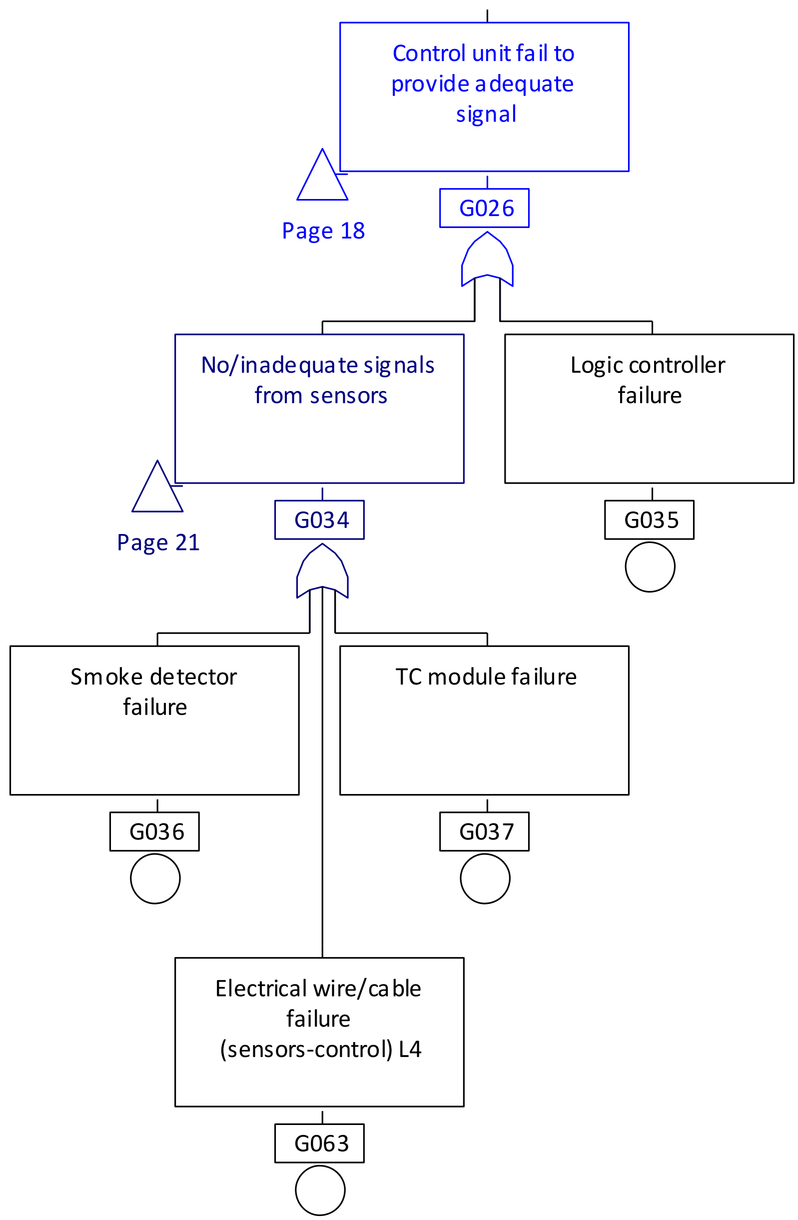

Figure 4-12: Unavailability tree for the wired SMART sprinklers – Subtree IV

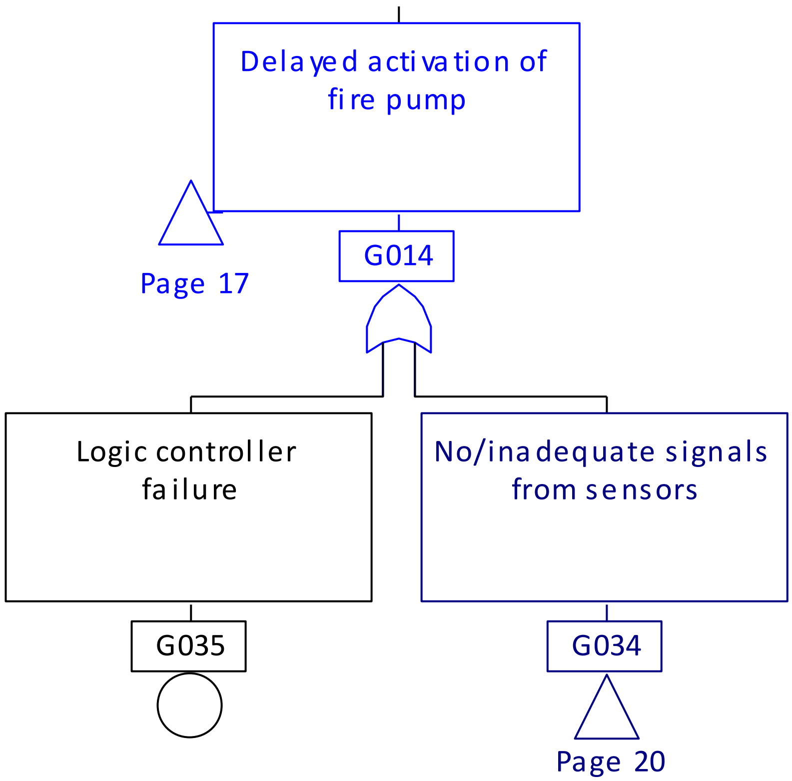

Figure 4-13: Unavailability tree for the wired SMART sprinklers – Subtree V

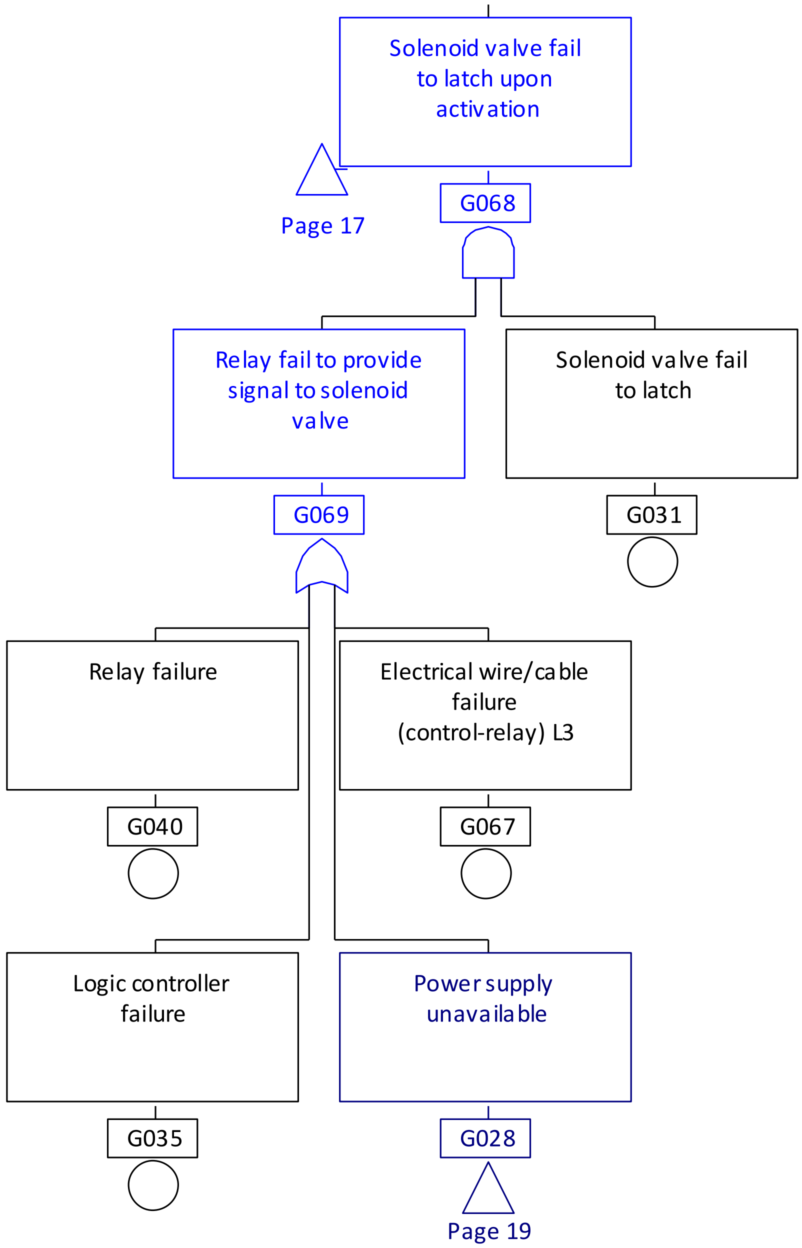

Figure 4-14: Unavailability tree for the wired SMART sprinklers – Subtree VI

4.2 Parameters for Reliability Distribution and ITM

For the components of the SMART sprinklers, this section provides the values of parameters for the reliability distribution and ITM.

4.2.1 Reliability Distribution

Reliability is the probability that a component performs as intended for a prescribed period of time when operated within the specified environmental and operating conditions. Inherent reliability depends on the design and manufacturing processes. However, the actual conditions in the field cannot be fully controlled, and can deviate from manufacturer's specifications. Therefore, in general, there are three broad categories of expected or unexpected failures that can affect the reliability of a component during its lifetime. They are: (1) early life or infant mortality failures that are caused by serious deficiencies in design and manufacturing processes; (2) random failures that are caused by unexpected causes such as extreme overstresses or human errors; and (3) aging-related failures that are caused by aging mechanisms such as wear, fatigue, and/or corrosion.

Weibull distributions are typically used for modeling reliability. Based on the Weibull distribution, the reliability, $R(t)$, at a component lifetime, t, can be estimated using Equation 4-1, where, β is the shape parameter and η is the characteristic life.

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \qquad \text{4-1}$$

4.2.1.1 Weibull Shape Parameter

The shape parameter value depends on the type of failure, e.g., if failure is caused due to serious design/manufacturing process deficiencies or human errors or overstresses or aging mechanisms. Table 4-1 provides the typical values of shape parameters for different types of failures.

Table 4-1: Typical values of shape parameters for different failure types

#	Failure type	Value of shape parameter
1	Serious design/manufacturing process deficiency related failures	< 1
2	Human error or overstress related random failures	≈ 1
3	Aging-related failures	> 1

To consider the range of failure types, probability distributions for shape parameters were determined in this study, and values were randomly sampled from the distributions. Accordingly, a distribution for the shape parameter with a mean value of 2.25 and a standard deviation of 0.5 was chosen for all the components except the wireless communication failure due to external interference and the power supply failure, for which a distribution with a mean value of 1 and a standard deviation of 0.1 was chosen. The values for the mean and standard deviation have been chosen to develop a distribution that can randomly generate all possible values representing all types of failures as discussed above. Therefore, for each of the components, ten values were randomly sampled from their respective distributions. Table 4-2 provides the randomly sampled values for the shape parameters for the components.

Table 4-2: Random values of shape parameters for components of SMART sprinklers

Components	Failure modes	Shape parameter values									
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Smoke detector	No/erroneous signal to transceiver module	2.2	2.2	1.6	1.4	2.3	2.2	2.3	2.2	2.8	1.9
Thermocouple (TC) module	No/erroneous signal to transceiver module	1.6	2.0	2.9	3.0	2.3	3.6	2.1	3.0	1.3	1.9
Signal transceiver module	Fail to act (i.e., communicate with master transceiver, and/or energize the relay when required)	3.3	2.0	2.2	1.9	2.0	1.7	1.8	1.5	2.9	2.1
Programmable logic controller	Fail to accurately infer severity and location of fire event for sprinkler activation	2.6	2.1	2.7	2.7	2.1	2.2	2.7	2.1	2.6	2.6
Master transceiver	Fail to act (i.e., communicate with signal transceiver module)	1.6	3.2	2.2	2.2	1.3	3.1	2.6	2.7	3.1	2.8
Wireless communication	Communication failure due to external interference	1.1	1.0	1.0	0.8	1.0	0.9	1.1	0.9	0.9	1.0
Electrical cable/wire	Fail to convey electrical signal	2.8	1.3	1.4	2.4	2.3	3.8	1.8	1.6	2.5	2.4
Power supply (back-up)	Unavailable	1.0	1.2	1.1	1.0	1.0	1.0	0.8	1.0	0.9	0.8
Relay	Fail to provide a path for energizing the solenoid valve	2.6	2.9	1.3	2.5	2.6	1.9	2.4	2.9	1.5	1.8
Solenoid valve	Fail to open	1.6	2.7	2.2	3.2	1.8	2.3	1.6	2.4	1.9	2.2
	Fail to latch	2.0	3.0	2.1	2.9	1.8	3.1	2.0	1.3	2.6	1.6
Open sprinkler	Fail to discharge (e.g., at intended pattern or flow rate)	2.5	1.9	2.3	2.0	1.6	2.9	2.0	2.6	2.1	3.1

4.2.1.2 Weibull Characteristic Life

The characteristic life is the lifetime at which the component reliability equals 0.368 (or 63.2% of the components fail). For a given shape parameter for a component, the reliability increases with an increase in the characteristic life.

In this study, the values of the characteristic life (η) were estimated based on the values of the MTBF and the shape parameters for the components, as shown in Equation 4-2, where, β is the Weibull shape parameter, and Γ is the Gamma function.

$$\eta = \frac{MTBF}{\Gamma\left(1+\frac{1}{\beta}\right)} \qquad 4\text{-}2$$

The MTBF for a component is the inverse of its failure rate. The probability is approximately 0.5 for a component to perform reliably (without failure) at the time when it reaches the MTBF value. For the components of the SMART sprinklers, the MTBF values have been adopted from reliability databases [10] [11], and past studies related to fire protection systems (e.g., [8] [9]). To characterize uncertainties with the MTBF values, probability distributions were considered, and values were randomly sampled to consider a range of failure rates. Table 4-3 provides the parameters of the MTBF distributions for the components.

Table 4-3: Parameter values for MTBF distributions for components of SMART sprinklers

Components	Failure modes	MTBF (years)			
		Mean	95% upper bound	95% lower bound	Standard deviation
Smoke detector	No/erroneous signal to transceiver module	12	15	9	1.5
Thermocouple (TC) module	No/erroneous signal to transceiver module	57	71	43	7.3
Signal transceiver module	Fail to act (i.e., communicate with master transceiver, and/or energize the relay when required)	28	35	21	3.6
Programmable logic controller	Fail to accurately infer severity and location of fire event for sprinkler activation	18	23	14	2.3
Master transceiver	Fail to act (i.e., communicate with signal transceiver module)	28	35	21	3.6
Wireless communication	Communication failure due to external interference	17.2	21	13	2.2
Electrical cable/wire	Fail to convey electrical signal	42	52	31	5.3
Power supply (main)	Unavailable	10^{-5} (probability of failure)			
Power supply (back-up)	Unavailable	7.3	9	5	0.9
Relay	Fail to provide a path for energizing the solenoid valve	65	81	49	8.2
Solenoid valve	Fail to open	19	24	14	2.4
	Fail to latch	15	19	11	2.0
Open sprinkler	Fail to discharge (e.g., at intended pattern or flow rate)	192	240	144	24.5

For each component, ten values were randomly sampled from their MTBF distribution. The random values of the MTBF and the shape parameter (see Table 4-2) were used to estimate the values of the characteristic life using Equation 4-2. Table 4-4 provides values of the characteristic life for the components.

Table 4-4: Values of characteristic life for the components of the SMART sprinklers

Component	Failure modes	Characteristic life (years)									
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Smoke detector	No/erroneous signal to transceiver module	14.0	13.2	12.6	13.2	8.3	13.6	13.4	14.9	11.7	13.3
Thermocouple (TC) module	No/erroneous signal to transceiver module	62.6	53.7	62.1	71.6	60.1	63.0	65.0	74.5	61.5	54.7
Signal transceiver module	Fail to act (i.e., communicate with master transceiver, and/or energize the relay when required)	26.9	32.0	38.4	25.2	33.1	28.2	33.3	26.3	30.0	38.5
Programmable logic controller	Fail to accurately infer severity and location of fire event for sprinkler activation	17.0	18.7	22.5	14.3	16.4	18.4	22.4	17.6	25.5	20.5
Master transceiver	Fail to act (i.e., communicate with signal transceiver module)	35.0	32.1	30.3	27.7	32.9	37.4	40.5	26.7	31.1	36.6
Wireless communication	Communication failure due to external interference	17.3	17.0	19.7	15.6	19.5	16.6	18.8	18.2	14.9	17.6
Electrical cable/wire	Fail to convey electrical signal	50.7	43.5	39.1	51.7	36.3	46.2	44.3	42.5	50.0	49.0
Power supply (back-up)	Unavailable	6.6	8.7	5.4	7.7	7.5	6.5	6.6	5.8	5.5	5.3
Relay	Fail to provide a path for energizing the solenoid valve	77.9	57.1	54.1	81.1	69.3	70.7	62.9	72.3	53.1	80.8
Solenoid valve	Fail to open	20.2	17.1	20.1	20.4	22.5	23.6	19.6	15.8	14.7	23.9
	Fail to latch	20.5	15.0	14.8	19.9	19.2	19.4	18.3	17.9	16.8	15.2
Open sprinkler	Fail to discharge (e.g., at intended pattern or flow rate)	256.9	232.5	242.0	220.8	175.8	253.0	219.1	209.5	197.5	238.9

4.2.2 Inspection/Testing/Maintenance (ITM)

The ITM parameters include inspection/testing frequency (or interval), maintenance durations, and restoration factors. The parameters have been determined based on review of relevant industry standards, as well as past studies related to fire protection systems.

4.2.2.1 Frequency/Interval

To determine the effects of inspection/testing frequencies on the availability of the system, two frequencies of annual and semi-annual were considered in this study for all the components of the SMART sprinklers. For the ITM frequencies of the components of the traditional wet sprinkler system, refer to Appendix A: Table A-1.

In this study, corrective[iv] maintenance (if necessary) at the time of inspection/testing has been considered. Some components (e.g., smoke detector and TC module) may be corrected upon failure based on sensor data received continuously by the PLC. However, for those components, not all failure modes can be detected through sensor data monitoring. For example, if the smoke detector fails to send signal, the PLC would be able to provide a warning. However, if the smoke detector detects smoke but

[iv] A corrective maintenance is usually performed to restore a failed system to an operational status by replacing or repairing the component that is responsible for the system failure.

sends anomalous signals to the PLC, then it cannot be possible for the PLC to detect anomalies and provide a warning (it would require an additional algorithm and a trained operator to detect such anomalies). Even a small anomaly in the signal has the potential to cause false activation or missed activation types of failures. Similarly, for a wireless SMART system, wireless communication failure due to external interference may be detected upon failure only for the case when no signal is received by the PLC. However, external interference can also cause noisy or anomalous signals, which cannot be detected upon failure by the PLC for the same reasons as described above. Therefore, this study considered a conservative case of corrective maintenance during inspection/testing.

4.2.2.2 Maintenance Duration

Maintenance duration depends on factors such as the extent of failure, the availability of spare parts (e.g., the lead times) and personnel for conducting maintenance, as well as the ease of conducting the maintenance. The maintenance durations have been considered based on review of relevant industry standards, and past studies related to fire protection systems. To characterize the uncertainty, distributions for maintenance duration were considered for the components. The durations for the scheduled/planned events such as fixed interval inspection/testing don't affect the system availability. Therefore, durations for the scheduled events were not considered in this study. Table 4-5 provides the distribution parameters.

Table 4-5: Distribution parameters for maintenance durations for SMART sprinklers

Components	Failure modes	Maintenance duration (days)	
		Mean	Standard deviation
Smoke detector	No/erroneous signal to transceiver module	3	1
Thermocouple (TC) module	No/erroneous signal to transceiver module	3	1
Signal transceiver module	Fail to act	7	2
Programmable logic controller	Fail to accurately infer severity and location of fire event for sprinkler activation	7	2
Master transceiver	Fail to act	7	2
Wireless communication	Communication failure due to external interference	3	1
Electrical cable/wire	Fail to convey electrical signal	3	1
Power supply (back-up)	Unavailable	3	1
Relay	Fail to provide a path for energizing the solenoid valve	3	1
Solenoid valve	Fail to open	3	1
	Fail to latch	3	1
Open sprinkler	Fail to discharge	7	2

For wireless communication failure, the maintenance duration reflects the time to detect and remove the source of external interference, and reactivate the wireless communication. For each of the components, ten values were randomly sampled from their respective distributions to consider all possible values, as shown in Table 4-6.

Table 4-6: Random values of maintenance durations for components of SMART sprinklers

Component	Failure modes	Maintenance durations (days)									
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Smoke detector	No/erroneous signal to transceiver module	2.7	3.5	3.1	1.9	4.4	2.4	1.7	1.0	3.4	1.6
Thermocouple (TC) module	No/erroneous signal to transceiver module	2.0	2.4	1.6	3.1	4.2	4.2	3.9	2.6	3.7	2.8
Signal transceiver module	Fail to act	8.0	9.1	6.2	9.0	6.3	9.6	3.9	7.6	5.5	4.8
Programmable logic controller	Fail to accurately infer severity and location of fire event for sprinkler activation	11.4	4.3	9.0	5.0	7.8	6.4	6.2	5.8	6.7	9.8
Master transceiver	Fail to act	1.2	6.3	3.9	6.5	7.3	6.1	7.6	8.1	3.7	5.3
Wireless communication	Communication failure due to external interference	1.3	4.0	4.5	2.9	1.4	2.9	3.8	2.6	1.8	3.3
Electrical cable/wire	Fail to convey electrical signal	4.0	1.0	3.4	4.0	3.4	3.6	4.1	2.0	3.7	4.3
Power supply (back-up)	Unavailable	3.7	4.0	3.9	3.5	2.3	2.9	2.7	4.5	4.2	2.7
Relay	Fail to provide a path for energizing the solenoid valve	3.5	2.8	2.3	2.1	0.8	2.6	1.3	4.5	3.1	4.0
Solenoid valve	Fail to open	3.0	3.2	1.7	4.4	2.1	0.0	1.9	0.6	3.3	3.3
	Fail to latch	1.2	3.1	5.1	1.3	2.6	1.1	4.4	2.6	3.5	3.8
Open sprinkler	Fail to discharge	6.7	6.0	7.1	11.0	7.6	8.0	8.0	6.1	8.1	6.0

4.2.2.3 Maintenance Restoration Factor

The restoration factor indicates the percentage (of new condition) to which a component will be restored after the performance of the maintenance action. For example, the value of the restoration factor indicates whether a component will be "as good as new" after the maintenance action (value = 1), or will not be improved at all (value = 0) but restored to operating condition. The restoration factor depends on the quality of the maintenance action (repair/replacement) and procedure, which in turn depends on the failure modes and the causes of the failures. For example, for a solenoid valve failure mode "fail to open" caused by wear/fatigue, the value of the restoration factor can be considered to be 1 if the maintenance action involves replacement by a new valve. No restoration has been considered during corrective ITMs if there is no failure and thus no need for a corrective maintenance.

To characterize the uncertainty, a distribution for the restoration factors with a mean of 0.5 and standard deviation of 0.3 was considered. For each component, ten values were randomly sampled from this distribution to consider all possible values. For the main power supply and the wireless communication (external interference), 100% restoration was considered for all maintenance actions.

4.3 Approximate Costs per Inspection/Testing and Maintenance of SMART Sprinklers to Estimate Lifetime ITM Costs

The lifetime costs of ITM can be divided into inspection/testing costs and maintenance costs. The inspection/testing portion of the lifetime ITM cost is estimated based on labor costs per inspection/testing of all the SMART sprinklers installed in a warehouse, and the total number of inspection/testing performed over the lifetime of 30 years; while the maintenance portion of the lifetime ITM cost is the sum total of the lifetime maintenance costs for all the components of the SMART sprinklers. A maintenance action is performed if a component is found to be in a degraded or failed state during a scheduled inspection/testing. Therefore, the lifetime maintenance costs for a component of the SMART sprinkler is estimated through the availability analysis based on the costs of maintaining the component, and the parameters for its reliability distribution and ITM.

The cost per inspection/testing is based on typical daily labor costs for technicians/engineers who are involved in determination of the condition of the components using test equipment or visual means as appropriate. It is assumed that the ITM companies have long term contracts with subsidized rates. Therefore, for inspection/testing, a cost of approximately $1000/day (for an eight hour day @ approximately $125/hour) was considered for 100 SMART sprinklers. It has been assumed that the inspection/testing of all the 500 SMART sprinklers in a warehouse will be conducted during a scheduled ITM (either annually or semi-annually).

The maintenance cost is divided into fixed and variable costs, and is considered on a per-component basis. The fixed cost is associated with the re-installation (of a component after maintenance) related labor costs (including ensuring that the entire system is operational again). In this study, a fixed cost of approximately $500 per component has been considered as a reasonable estimate irrespective of the type of component.

The variable cost is associated with fixing (i.e., repairing or replacing with a new one) a damaged component to bring it back to its operational status. Therefore, the variable cost depends on the cost of the component as well as whether repair or replacement action has been performed, which depends on the value of the restoration factor (refer to description of restoration factor in Section 4.2.2.3). The variable maintenance cost is considered to be less than or equal to the purchasing cost of a component.

Table 4-7 summarizes the approximate costs per inspection/testing and maintenance (rationale and postulates as described above).

Table 4-7: Approximate costs per inspection/testing and maintenance for SMART sprinklers

#	Item		Approximate costs	Description of costs
1	Inspection/testing cost		$5,000	Includes labor costs (including inspection/testing equipment costs) for inspection/testing of 500 SMART sprinklers during a scheduled inspection/testing
2	Maintenance	Fixed cost	$500	Includes re-installation related labor costs per component
3		Variable cost	Depends on ‘repair or replacement’, cost of component (Table 4-8)	

Table 4-8 provides the approximate costs considered in this study for the components of the prototype design of the SMART sprinklers.

Table 4-8: Approximate costs for the components of the SMART sprinklers

#	Component	Approximate costs ($ per unit)
1	Smoke detector	$20
2	Thermocouple (TC) module	$150
3	Signal transceiver module	$50
4	Programmable logic controller (PLC)	$500
5	Master transceiver	$500
6	Electrical wire	$10 (per connection)
7	Power supply (back-up)	$500
8	Relay	$50
9	Solenoid valve	$500
10	Open sprinkler	$100

Based on the approximate cost values provided in Table 4-8, the total costs of 500 SMART sprinklers (including the control unit and the back-up power supply) are estimated to be approximately $460,000 (for wireless configuration) and approximately $430,000 (for wired configuration). As described in Chapter 2 Section 2.4, there is one control unit (‘PLC + master transceiver’ for wireless configuration, and ‘PLC’ for wired configuration) and one back-up power supply per warehouse.

5. **Availability Analysis**

This chapter provides estimated availability values and lifetime ITM costs for the traditional wet sprinkler protection and the SMART sprinkler protection systems.

5.1 Availability of Traditional Wet Sprinkler and Wired/Wireless SMART Sprinkler Systems

The availability model for the SMART sprinklers (developed in Chapter 4) was used, instead of the one normally adopted for traditional sprinklers, to calculate the availability of a traditional wet sprinkler system. Thereafter, availability analysis was performed considering the random values of the reliability and ITM parameters for the components of the SMART sprinklers (as described in Chapter 4, Section 4.2). For comparison purposes, the following sections provide only the mean values of the availability. For the lower and upper bounds of the 90% confidence intervals, refer to Appendix B: Figures B-1 and B-2, and Table B-1.

Figure 5-1 compares the availability curves over time for the traditional wet sprinkler and the wired/wireless SMART sprinkler protection systems.

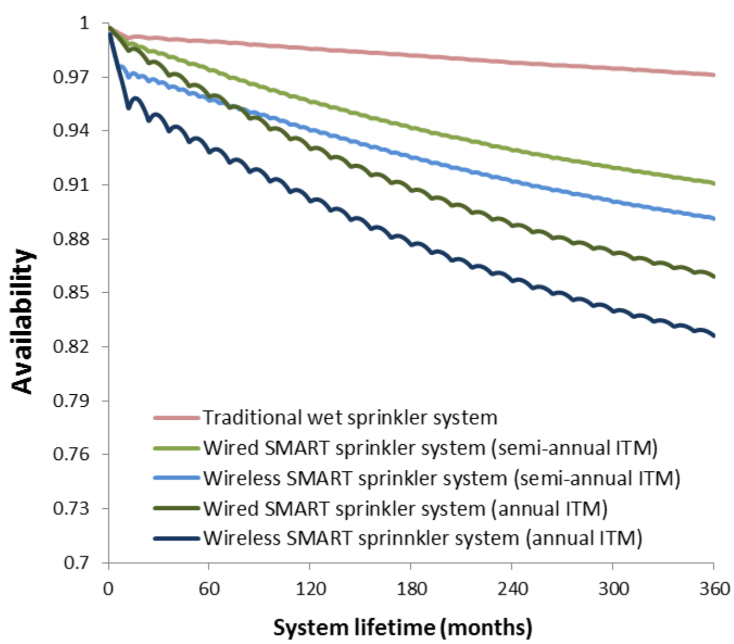

Figure 5-1: Availability curves over time for the traditional wet sprinkler and wired/wireless SMART sprinkler systems

Table 5-1 provides the availability values for the traditional wet sprinkler and the SMART sprinkler systems at 10, 20, and 30 years of life. In Table 5-1, a number within brackets indicates the percentage difference in the availability when compared to the availability of the traditional wet sprinkler system.

Table 5-1: Availability values for the traditional wet sprinkler protection and SMART sprinkler protection systems

Fire protection system	ITM frequency	Availability values		
		10 years	20 years	30 years
Traditional wet sprinkler system	'Current'[v]	≥ 0.9856	≥ 0.9779	≥ 0.9712
Wired SMART sprinkler system	Annual (SMART); 'current' (wet)	≥ 0.9301 (5.6%)	≥ 0.8874 (9.3%)	≥ 0.8590 (12.0%)
	Semi-annual (SMART); 'current' (wet)	≥ 0.9561 (3.0%)	≥ 0.9294 (5.0%)	≥ 0.9108 (6.0%)
Wireless SMART sprinkler system	Annual (SMART); 'current' (wet)	≥ 0.9013 (8.6%)	≥ 0.8569 (12.4%)	≥ 0.8261 (15.0%)
	Semi-annual (SMART); 'current' (wet)	≥ 0.9403 (4.6%)	≥ 0.9119 (6.7%)	≥ 0.8913 (8.0%)

Based on the uncertainty analysis (see Appendix B), the uncertainty in the availability of the SMART sprinkler system at the lifetime of 30 years was found to be approximately ±0.01.

5.2 Estimated Lifetime ITM Costs for Traditional Wet Sprinkler and Wired/Wireless SMART Sprinkler Systems

Appendix C provides the estimated lifetime ITM costs for the traditional wet sprinkler and the wired/wireless SMART sprinkler systems. The inspection/testing portion of the lifetime ITM costs has been estimated based on approximate labor costs per inspection/testing (as provided in Table 4-7 for the SMART sprinklers; and Table A-2 for the traditional wet sprinkler system) and the total number of inspection/testing performed over the lifetime of 30 years. The maintenance portion of the lifetime ITM costs is the sum total of the estimated lifetime maintenance costs for all the components. The lifetime maintenance costs for a component has been estimated through the availability analysis based on the fixed and variable costs of maintaining the component (refer to Tables 4-7 and 4-8 for the SMART sprinklers; and Tables A-2 and A-3 for the traditional wet sprinkler system), and the parameters for their reliability distribution and ITM.

The estimated lifetime ITM costs (Appendix C, Table C-4) were broken down into yearly values (for a lifetime of 30 years), and their PVs were estimated as shown in Table D-2 (Appendix D). Figure 5-2 shows the PV curves of cumulative ITM costs over time for the traditional wet sprinkler protection and the SMART sprinkler protection systems.

[v] The 'current' ITM frequency represents the frequencies used for the traditional wet sprinkler system in past studies (e.g., [8] [9]). Refer to Appendix A: Table A-1 for the 'current' ITM frequencies for the components of the traditional wet sprinkler system.

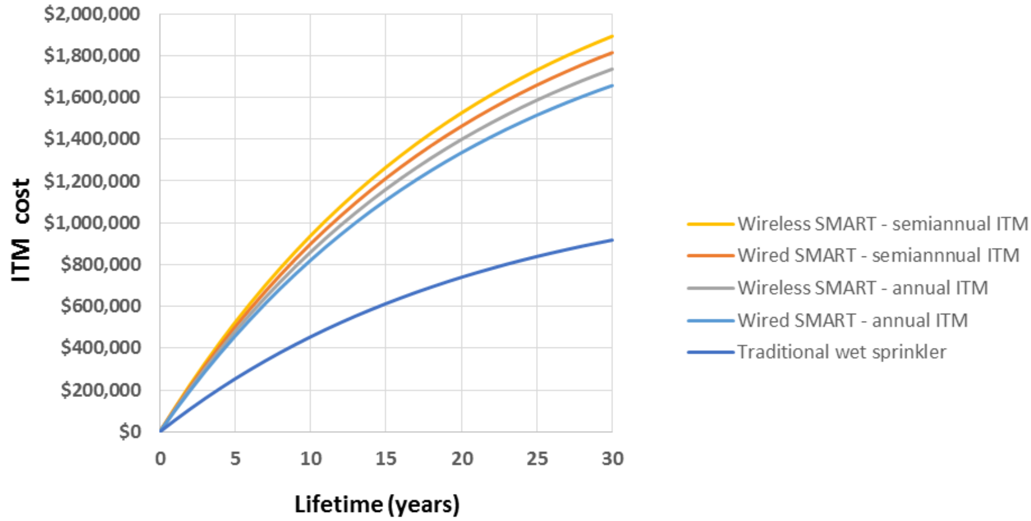

Figure 5-2: PV curves of cumulative ITM costs over time for traditional wet sprinkler protection and SMART sprinkler protection systems (cost figures refer to 500 head system)

5.3 Critical Components of Wired/Wireless SMART Sprinkler Systems

Figure 5-3 provides the critical components of the wired/wireless SMART sprinkler systems with respect to their percent contribution to the unavailability of the system.

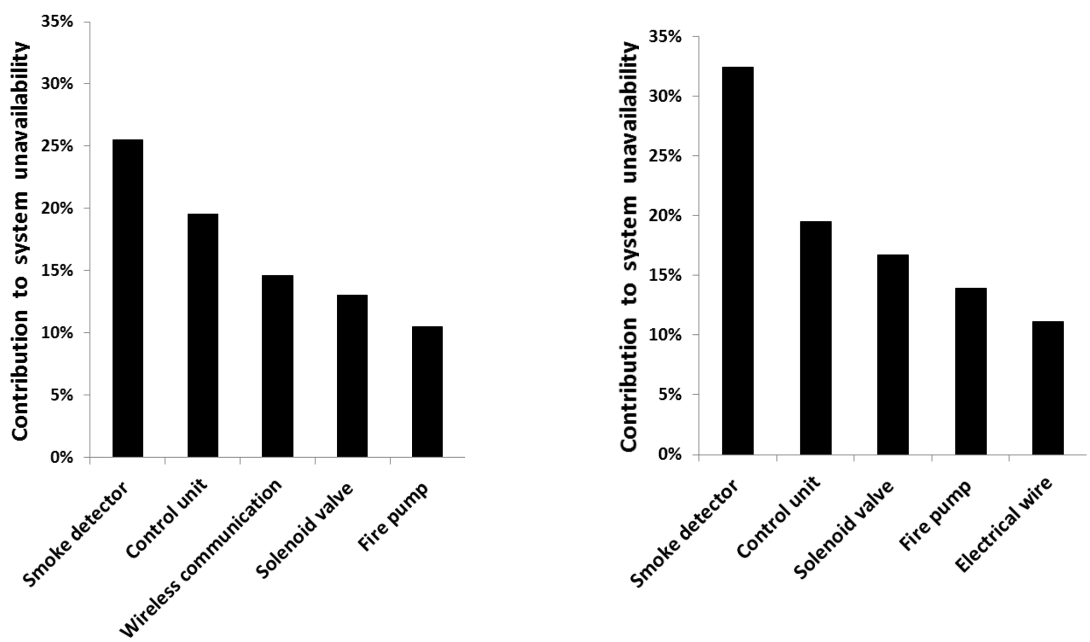

Figure 5-3: Critical components of wireless (Left) and wired (Right) SMART sprinkler systems

For both the wireless and the wired SMART sprinkler protection systems, the smoke detector is the most critical component because its MTBF value is the lowest (the back-up power supply has an even lower MTBF, but failure of the back-up power is conditional upon the failure of the main power supply). For the wireless SMART sprinkler protection system, the control unit (master transceiver and PLC) is the second ranked component followed by wireless communication (external interference), the solenoid valve (fail to open), and the fire pump (including water supply). For the wired SMART sprinkler protection system, the control unit (PLC) is the second ranked component followed by the solenoid valve (fail to open), the fire pump (including water supply), and electrical wires.

5.4 Discussion of Results

Due to less complexity and fewer components, the availability of the traditional wet sprinkler protection system is approximately 11% to 14% higher than those of the wired/wireless SMART sprinkler protection systems. In a similar fashion, the estimated lifetime ITM costs for the traditional wet sprinkler system is approximately 50% lower than those of the wired/wireless SMART sprinkler systems. The difference in the availabilities of the traditional wet sprinkler and the SMART sprinkler systems can be reduced by approximately 50% by increasing the ITM frequency of the SMART sprinklers from annual to semi-annual with relatively small increase (approximately 10%) in the estimated lifetime ITM costs. This is because the estimated lifetime ITM costs for 500 SMART sprinklers (in a warehouse) are dominated by the lifetime maintenance costs rather than the inspection/testing labor costs (refer to Appendix C for more details). Thus, an increase in the ITM frequency doesn't have much effect on the estimated lifetime ITM costs.

Due to the higher reliability of the wired connections, the unavailability of the wired SMART sprinkler system is approximately 20% lower than that of the wireless SMART sprinkler system. It should be noted that the availabilities of the SMART sprinkler systems are based on the reliability/ITM/criticality of all the components (including the water supply components such as fire pump). For example, both the wired and wireless SMART sprinkler systems contain the smoke detector and the solenoid valve, whose reliabilities are relatively poor and have much higher contributions (by a relative combined value of more than 40%) to the system unavailability. Therefore, when compared to the wireless SMART system, a 20% lower unavailability for the wired system is consistent with judgement or expectations.

6. Risk Estimation

In this study, risk is defined as the product of 'probability of occurrence of an undesired event' and 'severity of consequences associated with the undesired event'. For a warehouse with a protection system installed, the availability values estimated in Chapter 5 were used to estimate the risk, as shown in Equation 6-1. For details regarding the estimation of 'probability of fire', refer to Appendix D.

$$\begin{aligned} Risk_{with\ protection}(\$, t) \\ &= \left[Probability_{fire}(t) \times Unavailability_{protection\ sys}(t) \right. \\ &\quad \left. \times Severity\ of\ loss_{failed\ protection\ sys}(\$)\right] \\ &\quad + \left[Probability_{fire}(t) \times Availability_{protection\ sys}(t) \right. \\ &\quad \left. \times Severity\ of\ loss_{adequate\ protection}(\$)\right] \end{aligned} \tag{6-1}$$

For a warehouse without any protection system, the risk can be calculated using Equation 6-2.

$$Risk_{no\ protection}(\$, t) = Probability_{fire}(t) \times Severity\ of\ loss_{no\ protection}(\$) \tag{6-2}$$

For warehouses with and without protection systems, the loss severities (including for failed and adequate protection) are discussed in Chapter 2, Section 2.4. Based on Equations 6-1 and 6-2, the yearly values of the expected risk were calculated for warehouses 'with protection system' as well as 'with no protection'. The PVs of the yearly values of expected risk were then estimated based on Equation D-2 (Appendix D). For more details regarding the yearly estimates of risk and the PV, refer to Appendix D, Section D.4. Figure 6-1 shows the PV curves of cumulative risk over time.

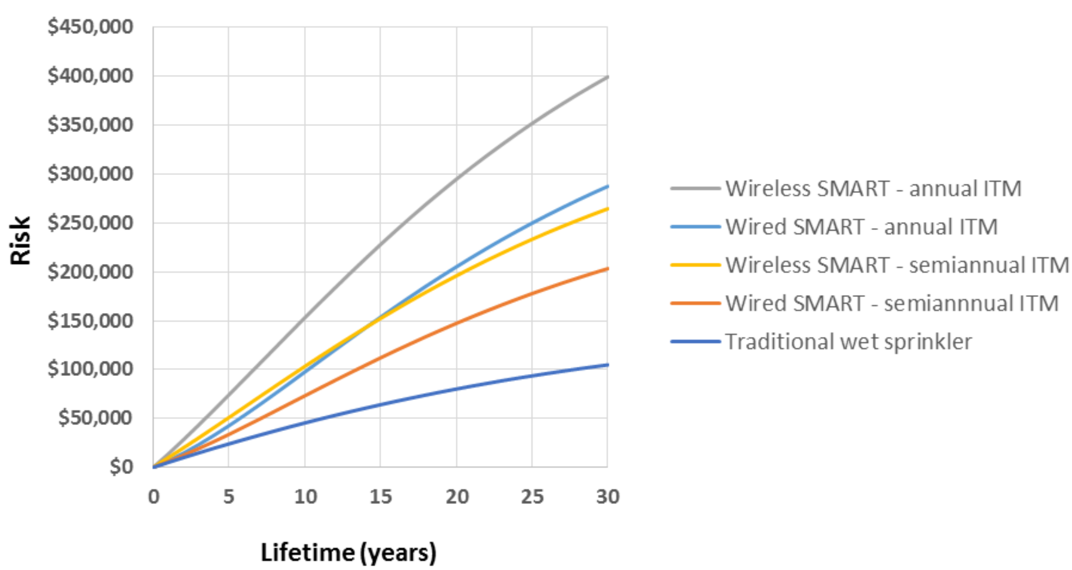

Figure 6-1: PV curves of cumulative risk over time for the traditional wet sprinkler protection and the SMART sprinkler protection systems

For a high storage configuration warehouse with a SMART sprinkler protection system installed, the estimated lifetime risk is highest (approximately $400,000) for the wireless system with annual ITM (lowest availability), whereas the estimated lifetime risk is lowest (approximately $200,000) for the wired system with semi-annual ITM. For a low storage configuration warehouse with a traditional wet sprinkler protection system installed, the estimated lifetime risk is approximately $100,000.

Figure 6-2 shows the PV curves of cumulative risk-reduction ($Risk_{no\ protection} - Risk_{with\ protection}$) over time for the traditional wet sprinkler protection and the SMART sprinkler protection systems.

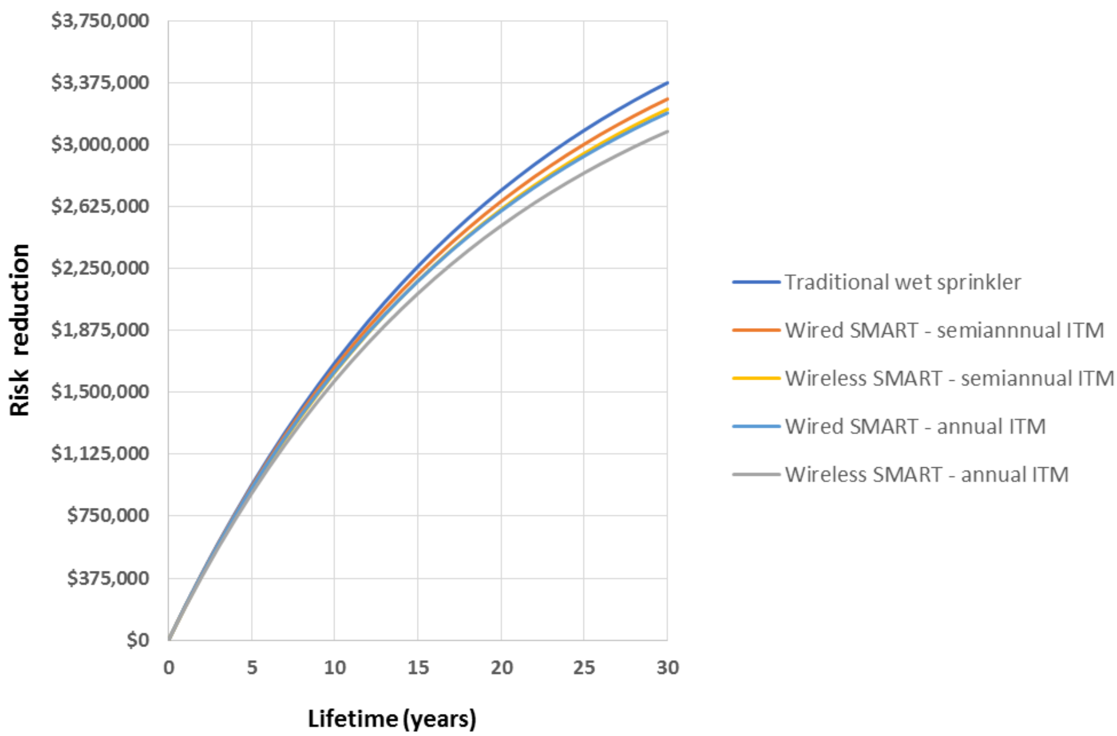

Figure 6-2: PV curves of cumulative risk-reduction over time for the traditional wet sprinkler protection and the SMART sprinkler protection systems

For the traditional wet sprinkler and the wired/wireless SMART sprinkler systems, the estimated lifetime risk-reductions are more than 90%. In Figure 6-2, the reduction in risk at time zero is the same for all systems. This is because the availability is assumed to be 100% for all the protection systems at time zero.

7. Cost-Benefit Analysis

In this study, the cost-benefit analysis has been performed using the cost-benefit model provided in the report [7] published by the National Institute of Standards and Technology (NIST). As per the NIST report, the generalized Present Value of Net Benefits (PVNB) can be estimated using Equation 7-1, where B_t is the dollar value of benefits in period t, C_t is the dollar value of costs in period t, T is the number of discounting time periods in the study period (lifetime of 30 years), and d is the discounting rate per time period (refer to Chapter 2, Section 2.4 for the discounting rate used in this study).

$$PVNB = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+d)^t} \tag{7-1}$$

A positive PVNB implies that the PV of benefits outweighs the PV of costs. In this study, ‘benefit’ is defined as the risk-reduction achieved from the use of a fire protection system, whereas ‘costs’ include ITM and initial installation costs for the fire protection system (refer to Appendix D, Table D-2 for the values of expected risk, initial installation and ITM costs, and the PVNB).

For the traditional wet sprinkler protection and the SMART sprinkler protection systems, Table 7-1 provides the estimated lifetime PVNBs.

Table 7-1: Estimated lifetime PVNBs for traditional wet sprinkler protection and SMART sprinkler protection systems

Fire protection system	ITM frequency	Estimated lifetime PVNB (approx.)
Traditional wet sprinkler	‘Current’	≈ \$2,177,699
Wired SMART sprinkler	Annual for SMART; ‘current’ for wet	≈ \$825,791
	Semi-annual for SMART; ‘current’ for wet	≈ \$752,678
Wireless SMART sprinkler	Annual for SMART; ‘current’ for wet	≈ \$605,229
	Semi-annual for SMART; ‘current’ for wet	≈ \$582,793

For the traditional wet sprinkler system installed in a low storage configuration warehouse, the estimated lifetime PVNB is approximately two to three times higher than those for the wired/wireless SMART sprinkler systems installed in a high storage configuration warehouse. For the SMART sprinkler system, the estimated lifetime PVNBs are comparable with annual and semi-annual ITMs. The estimated lifetime PVNB for the wired SMART sprinkler system is approximately 30% higher than the wireless system.

8. Conclusions

This study evaluated the availability of the wired/wireless SMART sprinkler protection systems for high storage configuration warehouses, and compared it with that of the traditional wet sprinkler protection system for low storage configuration warehouses. Further, this study conducted a comparative cost-benefit analysis for the SMART sprinkler protection and the traditional wet sprinkler protection systems.

While the availability of the traditional wet sprinkler system is 0.97 at the lifetime of 30 years, the availabilities of the SMART sprinkler systems are approximately 0.86±0.01 and 0.83±0.01, respectively, for the wired and wireless configurations. The higher availability of the traditional wet sprinkler system is due to lower complexity and fewer components when compared to the SMART sprinkler system. Due to higher reliability of the wired connections, the unavailability of the wired SMART sprinkler system is approximately 20% lower than that of the wireless SMART sprinkler system. The difference in the availabilities of the traditional wet sprinkler and the SMART sprinkler systems can be reduced by approximately 50% by increasing the ITM frequency of the SMART sprinklers from annual to semi-annual.

For both the traditional wet sprinkler and the SMART sprinkler systems, the estimated lifetime risk-reductions are more than 90%. The estimated lifetime ITM cost for the traditional wet sprinkler system is approximately 50% lower than those of the wired/wireless SMART sprinkler systems. For the traditional wet sprinkler system installed in a low storage configuration warehouse, the estimated lifetime PVNB is approximately two to three times higher than those for the wired/wireless SMART sprinkler systems installed in a high storage configuration warehouse. For the SMART sprinkler system, the estimated lifetime PVNBs with annual and semi-annual ITMs are comparable. The estimated lifetime PVNB for the wired SMART sprinkler system is approximately 30% higher than that of the wireless system.

The SMART sprinkler configuration used in this study is based on a proof-of-concept design, which is expected to change when used commercially (e.g., using an alternative to the solenoid valve or using a different activation mechanism or different sensors). Therefore, the values of the availability and the PVNB estimated in this study are only intended as general guidance and are expected to change according to actual system design and components.

In this study, the cost-benefit analysis has been performed with a limited objective of providing some comparative perspective into the costs and benefits associated with the SMART sprinkler and the traditional wet sprinkler protection systems. The results may be sensitive to the cost values considered in this study for components and ITM. Further, the results are expected to change based on the final (commercial) design of the SMART sprinkler system, and the location/facility where the SMART sprinklers are expected to be installed. Since the objective of the cost-benefit analysis was limited, a sensitivity (or uncertainty) analysis was not performed in this study for the cost-benefit estimates.

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Appendix A. Estimated Costs of ITM and Components of Traditional Wet Sprinkler System

As considered in this study (refer to Chapter 4 Section 4.3), the inspection/testing of all the 500 SMART sprinklers is expected to be conducted during a scheduled ITM (either annually or semi-annually). In comparison, the components of the traditional wet sprinkler system have different inspection/testing frequencies, as shown in Table A-1.

Table A-1: ITM frequencies ('current') for components of traditional wet sprinkler system

<table>
<tr><th>#</th><th>Component</th><th>ITM frequency</th></tr>
<tr><td>1</td><td>Controller</td><td rowspan="3">Weekly/annually</td></tr>
<tr><td>2</td><td>Electric motor</td></tr>
<tr><td>3</td><td>Fire pump</td></tr>
<tr><td>4</td><td>Piping</td><td>Upon failure</td></tr>
<tr><td>5</td><td>Check valves</td><td>Annually</td></tr>
<tr><td>6</td><td>Alarm check valve</td><td>Quarterly</td></tr>
<tr><td>7</td><td>Ball/gate/globe valves</td><td>Weekly/annually</td></tr>
<tr><td>8</td><td>Sprinklers</td><td>10 years</td></tr>
<tr><td>9</td><td>Public water supply</td><td>Upon failure</td></tr>
</table>

Table A-2 provides the approximate costs per inspection/testing and maintenance for the traditional wet sprinkler system that have been used to estimate its lifetime ITM costs. The same postulates used for determining the ITM costs for the SMART sprinklers (refer to Table 4-7) have also been used for the traditional wet sprinkler system. When compared to 500 SMART sprinklers, the inspection/testing of the traditional wet sprinkler system would involve only a few components (e.g., the fire pump and the ball valves during a weekly ITM; or the fire pump, the ball valves, and the check valves during an annual ITM) during a scheduled inspection/testing. Therefore, it has been considered that a scheduled inspection/testing of traditional wet sprinkler system can be completed in a day. Accordingly, a labor cost of approximately $1000/day (for an eight hour day @ approximately $125/hour) has been considered for a scheduled inspection/testing of the traditional wet sprinkler system.

The 'fixed' maintenance cost has been considered to be same as that for the SMART sprinklers (i.e., labor cost of approximately $500), while the 'variable' maintenance cost depends on the cost of the component and whether 'repair or replacement' action has been performed.

Table A-2: Approximate costs per inspection/testing and maintenance for traditional wet sprinkler system

#	Item		Costs (approx.)	Description of costs
1	Inspection/testing		$1,000	Includes labor costs (including inspection/testing equipment costs) per inspection/testing
2	Maintenance	Fixed cost	$500	Includes re-installation related labor costs per component
		Variable cost	Depends on 'repair or replacement', cost of component (Table A-3)	

Table A-3 provides approximate purchasing costs considered in this study for the components of the traditional wet sprinkler system. The cost of public water supply is not provided in Table A-3 because its maintenance is considered to be the responsibility of the town/city/state.

Table A-3: Approximate costs for the components of the traditional wet sprinkler system

#	Component	Approximate costs ($ per unit)
1	Controller	$5,000
2	Electric motor	$5,000
3	Fire pump	$5,000
4	Piping	$2,000
5	Check valve	$50
6	Alarm check valve	$100
7	Ball/gate/globe valves	$50
8	Sprinklers	$100

In Table A-3, the approximate cost values for the components (except that for the sprinklers which was considered to be the same as that of the sprinklers in Table 4-8) have been considered based on review of manufacturer websites and other online resources as well as with consideration of the installation costs for the traditional wet sprinkler system used in this study (refer to Chapter 2, Section 2.4). The costs of all the components of the traditional wet sprinkler system (including public water supply) are included in the installation costs. In this study, it has been considered that for large buildings such as warehouses, the labor costs for installation outweigh the purchasing costs for the components. Based on Table A-3, considering a warehouse with 500 traditional sprinklers, the total costs of components could be more than $75,000, which is approximately one-third of the total installation cost considered in this study.

The approximate cost values provided in Table A-3 could change based on the sprinkler layouts, water discharge flowrate requirements, and other protection configurations based on the actual design of the warehouse. Since both the traditional wet sprinkler system as well as the wired/wireless SMART sprinkler system use the same components for water supply, the cost values provided in Table A-3 can provide a comparative perspective into the costs and benefits associated with these systems.

Appendix B. Availability Values with Confidence Bounds

Corresponding to each of the ten random combinations (Chapter 4, Section 4.2) of reliability and ITM parameters for the components of the SMART sprinklers, the availability curves over time were generated. Thereafter, the 'standard error of the mean' method (used for small sample sizes) was used to determine the mean and 90% confidence bounds. The confidence bounds represent the expected variation in the mean availability.

B.1 Availability Values with Confidence Bounds for Wired/Wireless SMART Sprinkler Systems

Figures B-1 and B-2 provide the availability curves over time for wired and wireless SMART sprinkler systems, respectively.

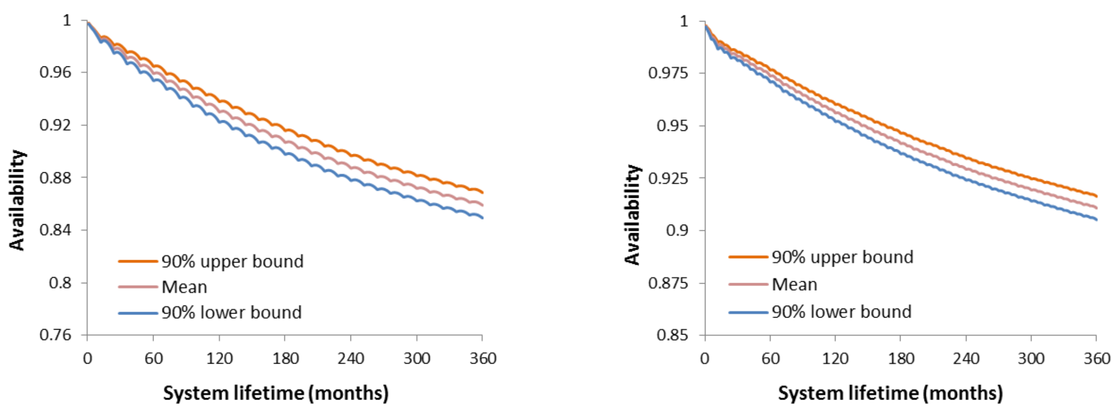

Figure B-1: Availability curves (with confidence bounds) over time for wired SMART sprinkler system (Left: Annual ITM; Right: Semi-annual ITM)

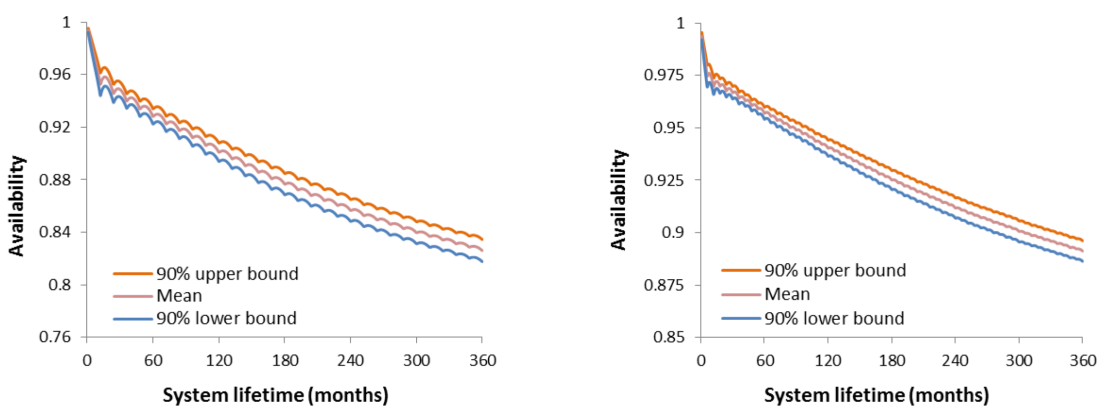

Figure B-2: Availability curves (with confidence bounds) over time for wireless SMART sprinkler system (Left: Annual ITM; Right: Semi-annual ITM)

B.2 Summary

Table B-1 provides the confidence bounds of the availability values as estimated in this study for the wired/wireless SMART sprinkler systems.

Table B-1: Availability values (confidence bounds) for wired/wireless SMART sprinkler systems

Protection system	ITM frequency	Availability values (90% lower bound – mean – 90% upper bound)		
		10 years	20 years	30 years
Wired SMART sprinkler system	Annual (SMART); 'current' (wet)	0.9223 – 0.9301 – 0.9380	0.8780 – 0.8874 – 0.8968	0.8494 – 0.8590 – 0.8687
	Semi-annual (SMART); 'current' (wet)	0.9521 – 0.9561 – 0.9602	0.9242 – 0.9294 – 0.9346	0.9052 – 0.9108 – 0.9164
Wireless SMART sprinkler system	Annual (SMART); 'current' (wet)	0.8943 – 0.9013 – 0.9083	0.8486 – 0.8569 – 0.8652	0.8177 – 0.8261 – 0.8345
	Semi-annual (SMART); 'current' (wet)	0.9365 – 0.9403 – 0.9442	0.9070 – 0.9119 – 0.9167	0.8864 – 0.8913 – 0.8961

Appendix C. Estimated Lifetime ITM Costs for Traditional Wet Sprinkler and SMART Sprinkler Systems

For the traditional wet sprinkler protection and the SMART sprinkler protection systems, this appendix provides the estimated lifetime ITM costs, which have been used to estimate the yearly ITM costs (including PV values) in Appendix D: Table D-2 and plot the PV curves of the ITM costs in Chapter 5, Section 5.2.

C.1 Estimated Lifetime ITM Costs

Table C-1 provides the estimated lifetime ITM costs for the traditional wet sprinkler system with the ITM frequencies as provided in Appendix A, Table A-1. During a scheduled ITM (e.g., weekly, quarterly, or annually), inspection/testing is expected to be conducted for all the components with the same ITM frequency (e.g., a weekly inspection/testing of the fire pump and the ball valves; or an annual inspection/testing of the check valves, the ball valves, and the fire pump). The inspection/testing costs are based on the ITM frequencies, e.g., weekly (total number of inspection/testing in a lifetime of 30 years is 53*30) or quarterly (total number of inspection/testing in a lifetime of 30 years is 4*30). Since the piping is expected to be maintained immediately 'upon failure', no additional cost for the inspection/testing of the piping was considered.

Table C-1: Estimated lifetime ITM costs for traditional wet sprinkler system in a warehouse with 500 sprinklers

#	ITM	Component	Estimated lifetime costs (approx.) per warehouse
1	Maintenance	All except sprinklers	$6,000
2		Sprinklers (500)	$1,500
3	Inspection/testing	Fire pump (including controller and motor), ball valves – weekly	53*30*1000 = $1,590,000
		Alarm check valve – quarterly	4*30*1000 = $120,000
		Fire pump (including controller and motor), ball valves, check valves – annually	1*30*1000 = $30,000
		Sprinklers – every 10 years	3*1000 = $3,000
4	Total lifetime ITM costs (approx.) per warehouse		≈ $1.75M

Table C-2 provides the estimated lifetime ITM costs for the wireless SMART sprinklers for both annual and semi-annual ITM frequencies. As discussed in Chapter 4, Section 4.3, the inspection/testing of all the 500 SMART sprinklers (both wired and wireless) is expected to be conducted during a scheduled ITM, i.e., either annually (total number of inspection/testing in a lifetime of 30 years is 30) or semi-annually (total number of inspection/testing in a lifetime of 30 years is 60).

Table C-2: Estimated lifetime ITM costs for wireless SMART sprinklers in a warehouse with 500 sprinklers

#	ITM	Component	Estimated lifetime costs (approx.)		Quantity per warehouse	Estimated lifetime costs (approx.) per warehouse	
			Annual ITM	Semi-annual ITM		Annual ITM	Semi-annual ITM
1	Maintenance	PLC	$1,400	$1,600	1	$1,400	$1,600
2		Master transceiver	$400	$500	1	$400	$500
3		Wireless communication	$700	$800	1	$700	$800
4		Back-up power supply	$4,000	$4,500	1	$4,000	$4,500
5		Remaining components (per SMART sprinkler)	$2,800	$3,100	500	$2,800*500 = $1.40M	$3,100*500 = $1.55M
6	Inspection/testing	All components of SMART sprinklers installed in a warehouse				$5,000*30 = $150,000	$5,000*60 = $300,000
7	Total lifetime ITM costs (approx.) per warehouse					≈ $1.56M	≈ $1.86M

Table C-3 provides the estimated lifetime ITM costs for the wired SMART sprinklers for both annual and semi-annual ITM frequencies.

Table C-3: Estimated lifetime ITM costs for wired SMART sprinklers in a warehouse with 500 sprinklers

<table>
<tr><th rowspan="2">#</th><th rowspan="2">ITM</th><th rowspan="2">Component</th><th colspan="2">Estimated lifetime costs (approx.)</th><th rowspan="2">Quantity per warehouse</th><th colspan="2">Estimated lifetime costs (approx.) per warehouse</th></tr>
<tr><th>Annual ITM</th><th>Semi-annual ITM</th><th>Annual ITM</th><th>Semi-annual ITM</th></tr>
<tr><td>1</td><td rowspan="3">Maintenance</td><td>PLC</td><td>$1,400</td><td>$1,600</td><td>1</td><td>$1,400</td><td>$1,600</td></tr>
<tr><td>2</td><td>Back-up power supply</td><td>$4,000</td><td>$4,500</td><td>1</td><td>$4,000</td><td>$4,500</td></tr>
<tr><td>3</td><td>Remaining components (per SMART sprinkler)</td><td>$2,500</td><td>$2,800</td><td>500</td><td>$2,500*500 = $1.25M</td><td>$2,800*500 = $1.40M</td></tr>
<tr><td>4</td><td>Inspection/testing</td><td colspan="4">All components of SMART sprinklers installed in a warehouse</td><td>$5,000*30 = $150,000</td><td>$5,000*60 = $300,000</td></tr>
<tr><td>5</td><td colspan="5">Total lifetime ITM costs (approx.) per warehouse</td><td>≈ $1.41M</td><td>≈ $1.71M</td></tr>
</table>

C.2 Discussion of Results

The estimated lifetime ITM costs for 500 wired/wireless SMART sprinklers (as provided in Tables C-2 and C-3) is dominated by the lifetime maintenance costs for the components, rather than the inspection/testing labor costs; while the estimated lifetime ITM costs for the traditional wet sprinkler system (as provided in Table C-1) is dominated by the inspection/testing labor costs. This is because the inspection/testing of all the 500 SMART sprinklers is expected to be conducted during a scheduled ITM (either annually or semi-annually); on the other hand, the inspection/testing frequencies are different for different components of the traditional wet sprinkler system thereby incurring substantial inspection/testing labor costs. Furthermore, each SMART sprinkler comprises of more than five components, thus incurring substantial lifetime maintenance costs overall for 500 SMART sprinklers installed in a warehouse.

The lifetime ITM costs for the SMART sprinkler protection system includes the lifetime ITM costs for the SMART sprinklers and for the traditional wet sprinkler system. Table C-4 provides the estimated lifetime ITM costs for the traditional wet sprinkler and the SMART sprinkler protection systems.

Table C-4: Estimated lifetime ITM costs for traditional wet sprinkler and SMART sprinkler systems

Protection system	ITM frequency	Estimated lifetime ITM costs (approx.)
Traditional wet sprinkler system	'Current'	≈ 1.75M
Wired SMART sprinkler system	Annual (SMART); 'current' (wet)	≈ 3.16M
	Semi-annual (SMART); 'current' (wet)	≈ 3.46M
Wireless SMART sprinkler system	Annual (SMART); 'current' (wet)	≈ 3.31M
	Semi-annual (SMART); 'current' (wet)	≈ 3.61M

For the traditional wet sprinkler system, the estimated lifetime ITM costs are approximately 50% lower than those of the wired/wireless SMART sprinkler systems.

Appendix D. Equations/Data for Risk Estimation and Cost-Benefit Analysis

This appendix provides the equations and data that have been used to plot the estimated lifetime ITM costs in Chapter 5 and the risk curves in Chapter 6, and evaluate the PVNBs in Chapter 7.

D.1 Probability of Fire

The ‘probability of fire’ can be modeled based on a Poisson distribution [12] [13]. The probability of occurrence of ‘χ’ fires in a time interval, T, can be calculated using Equation D-1, where λ represents the fire frequency.

$$P_{fire} = \frac{\exp(-\lambda T) \times (\lambda T)^{\chi}}{factorial(\chi)} \qquad \text{D-1}$$

D.2 Present Value of Money

The present value (PV) of a sum of money at a future time, C_t, is calculated using Equation D-2, where d is the discounting rate.

$$PV = \frac{C_t}{(1+d)^t} \qquad \text{D-2}$$

D.3 Availability Values (updated for renewal upon reinstallation after fire occurrence)

After fire occurrence, the protection system needs to be reinstalled in the warehouse. Therefore, the availability of the protection system is renewed to a value of 1 (age = 0 years). To account for this renewal, Monte Carlo simulation (100,000) was performed using the software package Oracle® Crystal Ball to estimate the averaged availability values (based on original values provided in Chapter 5, Section 5.1) considering the expected number of fires over the lifetime of the protection system (fire frequency of 0.025/year). Table D-1 provides the updated availability values for the traditional wet sprinkler and the SMART sprinkler protection systems.

Table D-1: Updated availability values for traditional wet sprinkler protection and SMART sprinkler protection systems

Fire protection system	ITM frequency	Availability values		
		10 years	20 years	30 years
Traditional wet sprinkler system	'Current'	≥ 0.9868	≥ 0.9816	≥ 0.9781
Wired SMART sprinkler system	Annual (SMART); 'current' (wet)	≥ 0.9379	≥ 0.9088	≥ 0.8940
	Semi-annual (SMART); 'current' (wet)	≥ 0.9608	≥ 0.9426	≥ 0.9329
Wireless SMART sprinkler system	Annual (SMART); 'current' (wet)	≥ 0.9091	≥ 0.8789	≥ 0.8627
	Semi-annual (SMART); 'current' (wet)	≥ 0.9453	≥ 0.9260	≥ 0.9150

D.4 Expected Risk, ITM Costs, and PVNB (Yearly Values)

Table D-2 provides the initial installation costs (approximate) for the fire protection systems, and estimated yearly values of the probability of fire, the risk, the ITM costs, and the PVNBs. To support page size requirements, only the values for every five years (starting from zero year and ending at 30 years) have been provided in Table D-2 (Note: the yearly values in the table are at the time indicated such as at 5 years, and are not the cumulative values except for the PVNB, which is defined as such in Chapter 7).

As discussed in Chapter 2, Section 2.4, the installation costs for the SMART sprinkler system in a warehouse include the purchasing costs for 500 SMART sprinklers and the installation costs for the traditional wet sprinkler system (approximately $280,000). No additional labor cost is considered for installation of the SMART sprinklers. Refer to Chapter 4, Section 4.3 for the purchasing costs of 500 SMART sprinklers (approximately $430,000 for wired configuration, and approximately $460,000 for wireless configuration).

The probability of fire has been estimated using Equation D-1 for a period of one year. The risk values have been estimated using Equations 6-1 (with protection) and 6-2 (no protection). The approximate yearly ITM costs were estimated by breaking down the estimated lifetime ITM costs (as provided in Appendix C, Table C-4) into yearly values (for a lifetime of 30 years). For the risk and the ITM costs, the PV values were estimated using Equation D-2 (with a discount rate of 4.8%, refer to Chapter 2, Section 2.4). The PVNB values were estimated using Equation 7-1.

Table D-2: Yearly values (approximate) of estimated risk, ITM costs, and PVNB for traditional wet sprinkler protection and SMART sprinkler protection systems

Year →		0	5 years	10 years	15 years	20 years	25 years	30 years
Occurrence probability of a fire in time interval of a year		**0**	**0.025**	**0.025**	**0.025**	**0.025**	**0.025**	**0.025**
Roll paper warehouse: Property + outage costs (excluding protection system)		**$17,700,000**						
Installation costs of wired SMART sprinkler protection system		**$710,000**						
Installation costs of wireless SMART sprinkler protection system		**$740,000**						
Installation costs of traditional wet sprinkler protection system		**$280,000**						
Warehouse with no protection	**Expected risk (yearly values)**	0	$221,250	$221,250	$221,250	$221,250	$221,250	$221,250
	PV of expected risk (yearly values)	0	$175,016	$138,443	$109,513	$86,628	$68,525	$54,206
Warehouse with wired SMART sprinkler system – annual ITM	**Expected risk (yearly values)**	0	$12,558	$18,162	$22,118	$25,014	$27,015	$28,499
	PV of expected risk (yearly values)	0	$9,934	$11,365	$10,948	$9,794	$8,367	$6,982
	ITM costs of protection system (yearly values)	0	$105,333	$105,333	$105,333	$105,333	$105,333	$105,333
	PV of ITM costs (yearly values)	0	$83,322	$65,910	$52,137	$41,242	$32,624	$25,806
	PVNB	-$710,000	-$248,001	$96,245	$355,990	$554,290	$707,134	$825,791
Warehouse with wired SMART sprinkler system – semiannual ITM	**Expected risk (yearly values)**	0	$9,356	$12,770	$15,242	$17,055	$18,398	$19,339
	PV of expected risk (yearly values)	0	$33,772	$73,210	$112,042	$147,273	$177,757	$203,314
	ITM costs of protection system (yearly values)	0	$115,333	$115,333	$115,333	$115,333	$115,333	$115,333
	PV of ITM costs (yearly values)	0	$91,232	$72,167	$57,087	$45,157	$35,721	$28,256
	PVNB	-$710,000	-$282,661	$42,655	$292,354	$485,361	$635,420	$752,678
Warehouse with wireless SMART sprinkler system – annual ITM	**Expected risk (yearly values)**	0	$19,720	$25,011	$29,145	$32,145	$34,365	$35,972
	PV of expected risk (yearly values)	0	$15,599	$15,650	$14,426	$12,586	$10,644	$8,813
	ITM costs of protection system (yearly values)	0	$110,333	$110,333	$110,333	$110,333	$110,333	$110,333
	PV of ITM costs (yearly values)	0	$87,277	$69,039	$54,612	$43,200	$34,172	$27,031
	PVNB	-$740,000	-$331,394	-$28,140	$199,060	$371,332	$503,288	$605,229
Warehouse with wireless SMART sprinkler system – semiannual ITM	**Expected risk (yearly values)**	0	$13,248	$16,461	$19,059	$21,020	$22,508	$23,618
	PV of expected risk (yearly values)	0	$10,480	$10,300	$9,434	$8,230	$6,971	$5,786
	ITM costs of protection system (yearly values)	0	$120,333	$120,333	$120,333	$120,333	$120,333	$120,333
	PV of ITM costs (yearly values)	0	$95,187	$75,296	$59,561	$47,115	$37,269	$29,481
	PVNB	-$740,000	-$351,669	-$56,357	$169,481	$343,314	$477,971	$582,793
Warehouse with traditional wet sprinkler system	**Expected risk (yearly values)**	0	$5,765	$6,506	$7,113	$7,675	$8,079	$8,461
	PV of expected risk (yearly values)	0	$4,560	$4,071	$3,521	$3,005	$2,502	$2,073
	ITM costs of protection system (yearly values)	0	$58,333	$58,333	$58,333	$58,333	$58,333	$58,333
	PV of ITM costs (yearly values)	0	$46,143	$36,501	$28,873	$22,840	$18,067	$14,291
	PVNB	-$280,000	$405,191	$944,872	$1,369,994	$1,705,028	$1,969,232	$2,177,699

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