CI/SfB

| | | | (K5)

June 1996

BRANZ
THE RESOURCE CENTRE FOR BUILDING EXCELLENCE

STUDY REPORT

No. 66 (1996)

Effectiveness of Smoke Management Systems

P. Narayanan

The work reported here was funded jointly by the Building Research Levy and the Foundation for Research, Science and Technology from the Public Good Science Fund.

ISSN: 0113-3675

Preface

This report on a study carried out at BRANZ details the risk assessment approach adopted in evaluating the effectiveness of smoke management systems. The report is intended for designers of smoke management systems.

Acknowledgements

This work was funded by the Building Research Levy and the Foundation for Research Science and Technology from the Public Good Science Fund.

Readership

This report is intended for fire protection engineers and fire researchers.

EFFECTIVENESS OF SMOKE MANAGEMENT SYSTEMS

BRANZ Study Report No 66 P. Narayanan

REFERENCE

P. Narayanan, 1996. *Effectiveness of Smoke Management Systems. Building Research Association* of New Zealand. Study Report No 66. Judgeford, New Zealand.

KEYWORDS

Computer Software; Building Fires; Fire Spread; Smoke; Smoke Dampers; Smoke Detection Systems.

ABSTRACT

Traditional design of smoke management systems (SMS) aims at providing smoke exhaust capacity based on maintaining the design smoke and air flow rates at critical locations in the building, and by providing additional capacity or redundant components to cover failure of critical components in the system.

This approach assumes 100 percent reliability in the performance of individual elements in the SMS and fully effective interaction between these elements. Such designs often fail to provide the assurance that the SMS will:

- Become functional in the event of an emergency
- Carry out the design objectives effectively for the full required duration.

A risk assessment approach based on subjective probabilities has been adopted in this study to evaluate the effectiveness of the SMS. A checklist approach with probability assignment based on experience or engineering judgement has been adopted.

A framework for a simple computer risk assessment model has been proposed. Provision has been made within this framework for modification of probability values by users, based on their individual experiences.

Contents

Figures

Tables

1. INTRODUCTION

1.1 Background

Smoke inhalation during fires is widely accepted as the primary cause of death (Berl, 1980). Although the number of fire deaths in high-rise buildings is small (Narayanan and Whiting, 1996), the number of fires that occur in these buildings poses significant potential for fire related injuries. Failure of smoke management systems (SMS) in buildings to manage smoke spread either through poor performance or inadequate design, is often cited as the main reason for these injuries.

The effectiveness of smoke management systems (SMS) in buildings where complexities arise due to the nature of floor plans and unknown gaps between firecells relies not only on the accuracy with which the movement of smoke and air can be predicted but also the effectiveness of the overall smoke management system (SMS) and its ability to perform as designed.

The primary objectives of a smoke management system (NFPA 92B, 1991) include:

- Maintaining the smoke layer interface above a predetermined elevation
- Maintaining a tenable environment in all exit access and area of refuge access paths for a sufficient time to allow the safe evacuation of all occupants
- Limiting the spread of smoke from the fire/smoke zone into safe exit paths
- Providing adequate visibility to allow Fire Service personnel to conduct their firefighting activities
- Exhausting accumulated smoke within a specified time
- Limiting the smoke layer temperature.

The term SMS as used in this report refers to all processes used, independently or in combination, to affect smoke movement for the safety of occupants and firefighting personnel and for the reduction of property damage (Sfintesco et al, 1992).

Traditional design of smoke management systems is based on the use of passive smoke control systems, such as doors, walls and floors, in combination with active smoke control systems, such as extract fans, to create pressure differences that would facilitate the movement of smoke away from safe areas. The design of the mechanical smoke extraction systems relies on providing a smoke exhaust capacity based on:

- The number of air changes required to maintain flow rates at critical locations in the building
- Provision of additional capacity to cover for failures of system components
- Effective interface between the active and passive systems, along with 100% reliability after commissioning.

If the SMS performs as designed, the additional capacity could make it a super-efficient system. In super-efficient systems (Marchant, 1990) the outward flow exceeds the critical volume flow rate for the design depth of smoke layer. This causes turbulence and entrainment of clean air from the lower layer, causing the smoke layer to further increase in volume and depth.

When SMS fail to perform as designed, the ultimate result is the rapid deterioration of tenability conditions in the building.

Active systems consist of components, such as smoke detection devices, mechanical smoke curtains, smoke dampers and other HVAC systems. In many cases the lack of understanding of the ability of individual components to perform as a system and the interaction of active systems with other passive systems, has led to failure and often excessive design without any guarantee that such a system:

- Will be activated during an emergency, and
- Will perform as designed.

Currently available fire engineering design guides for smoke management systems (Buchanan, 1994 ; Klote, 1992) acknowledge similar concerns.

1.2 Objectives

Approved Document C3/AS1 of the New Zealand Building Code (Building Industry Authority, 1992) sets the following broad performance requirements for some parts of the SMS:

- Air conditioning and mechanical ventilation systems shall be constructed to avoid circulation of smoke and fire between firecells

- Where automatic smoke control systems are installed they shall be constructed to:

  - avoid the spread of fire and smoke between firecells, and
  - protect escape routes from smoke until the occupants have reached a safe place

- The SMS, as part of the fire safety system, is required to facilitate the specific needs of firefighters to:

  - carry out rescue operations, and
  - control the spread of fire.

The broad nature of these performance requirements does not provide an adequate basis for the design of an effective SMS that will contribute to overall fire safety in buildings. The objectives of the research covered in this report therefore is to :

- Identify and examine factors that influence the performance and reliability of the components of SMS in buildings
- Apply risk assessment techniques to develop a checklist approach for evaluating the effectiveness of SMS
- Develop a framework for a simple computer model to be used to evaluate SMS effectiveness.

2. RISK ASSESSMENT APPROACH FOR SMS

2.1 System Effectiveness

System effectiveness is often related to system reliability. System reliability is defined as the probability of performing a specific function or mission under design conditions for a given period of time. To ascertain the effectiveness of any system the following aspects of subsystems must be studied:

- Reliability
- Capability, ie. the design adequacy in achieving the operational demand satisfactorily under specified conditions
- Availability or operational readiness.

Reliability analysis can be applied to any system where each individual component contributes in some form to the probability that the system will perform its function over the required duration (Bowen, 1988). Traditionally, information on reliability of fire safety systems has been based on protection of property rather than on life safety (Richardson, 1985).

Reliability information for fire safety systems is vital for a probabilistic approach to fire safety design. However, generation of such information based on a purely statistical approach can be cumbersome and not cost effective. Studies on the reliability approach to fire safety carried out at Lund University (Pettersson and Jonsson, 1988) have identified similar difficulties. The following levels of reliability analysis were identified for the integration of probabilistic models with physical models:

- The exact evaluation of the likelihood of failure using multi-dimensional integration or Monte Carlo simulation
- Approximate evaluation of the failure probability based on First Order Reliability Methods (FORM) or
- A practical design format calculation based on partial safety factors and taking into account characteristic values for action effects and response capacities.

The more simplified practical design formats (last point above) were preferred for the following reasons:

- Exact evaluation of probabilistic failure was found not to be practicable
- FORM approximations were cumbersome for everyday use.

Risk assessment approaches often depend on the designer's use of subjective probabilities based on his/her knowledge, experience and confidence levels. Thus variations in the output must be expected between two individuals using the same model or approach.

On the other hand, any risk assessment method used by an experienced person to evaluate the reliability and performance standards of various design options will improve his/her selection of :

- Levels of life safety
- Cost-effective solutions

Life safety objectives in the design of SMS are achieved through maintaining the smoke layer interface at a certain height to maintain tenability for a required duration. The reliability with which this can be maintained is dependent on the effectiveness of the functioning of the individual components and their effective interaction.

The components (subsystems) of an effective Smoke Management System (SMS) are shown in Figure 1. Detailed discussion and modelling of individual subsystems are carried out in Chapters 3 and 4 of this report.

2.2 Risk Assessment Approach

A risk assessment approach using network diagrams is adopted in this study.

Network Diagrams: Network diagrams are logic diagrams that identify casual events that lead to failure of the subsystem (Fitzgerald, 1991). The network diagram as shown by the example in Figure 2 describes a status at a point in time by:

- Identifying success conditions
- Using deductive logic, and
- Breaking down a success event in greater detail.

2.3 Reliability Modelling

Fire safety systems can be treated as subsystems functioning in series, parallel or a combination of both serial and parallel components (Bowen, 1988). The model used in this study considers only a series combination of components.

2.3.1 Series System

Components (subsystems) which on failure lead to failure of the system can be modelled as being in series. If each component's failure is independent of the others, system reliability for components in series is given by the expression:

$$\mathbf{R}_{sys} = \mathbf{R}_1 \times \mathbf{R}_2 \times \ldots\ldots \times \mathbf{R}_n \qquad \text{Equation 2.1}$$

where $\mathbf{R}_i$ = Probability that component i, is effective.

In a series electrical circuit as shown in Figure 3, current flow is impeded if any switch is open. Using this analogy the failure of any series system can be approximated such that event **n** will not occur if event 1,2 or 3 fail.

In using this approach the system reliability will be no greater than that of the least reliable component (Bowen, 1988).

2.4 Probabilities

2.4.1 Probability Assignment

In developing a measure of effectiveness, the impact levels of failure of each element to perform as designed on the overall smoke management system are examined. The level of effectiveness of the SMS is greatly influenced by the rate of fire development in the firecell. To incorporate this effect the fire scenarios are categorised as:

- Smouldering
- Non-flashover
- Flashover

Based on these categories, probabilities are assigned for each individual element in the SMS, based on whether the reliability is:

- High
- Medium, or
- Low.

The success probabilities assigned to each element, although arbitrary, are based on confidence levels from experience. Provision has been made in the computer program derived later for users to modify these factors based on their experience in the field (see Chapter 4).

2.4.2 Probability Calculation

The two rules for the probability of an outcome (Fitzgerald, 1991) are:

- Multiplication of the probabilities along a continous path gives the probability of an outcome of that path
- Addition of like outcomes gives the total result for that outcome.

3. SUBSYSTEMS IN SMS

3.1 Active and Passive Subsystems in SMS

The contribution of the components of the control system to the overall effectiveness of any smoke management system in the building is based on the reliability of each component (subsystem) in the system. The failure of each subsystem to perform as designed influences the reliability of SMS to varying extents.

For the purpose of this report the subsystems are categorised as active or passive subsystems. Active subsystems rely on detectors and other signalling devices for their activation. Those that are not directly activated by signalling systems have been categorised as passive subsystems. Figure 4 is a diagrammatic representation of the contributions of the various subsystems.

The processes and events in each subsystem are discussed in this section. The reliability and performance aspects or events are identified and probabilities assigned based on the impact on their overall SMS. Table 1 shows the 8 main subsystems in the SMS and their components.

Figure 1 : Subsystems in an Effective SMS

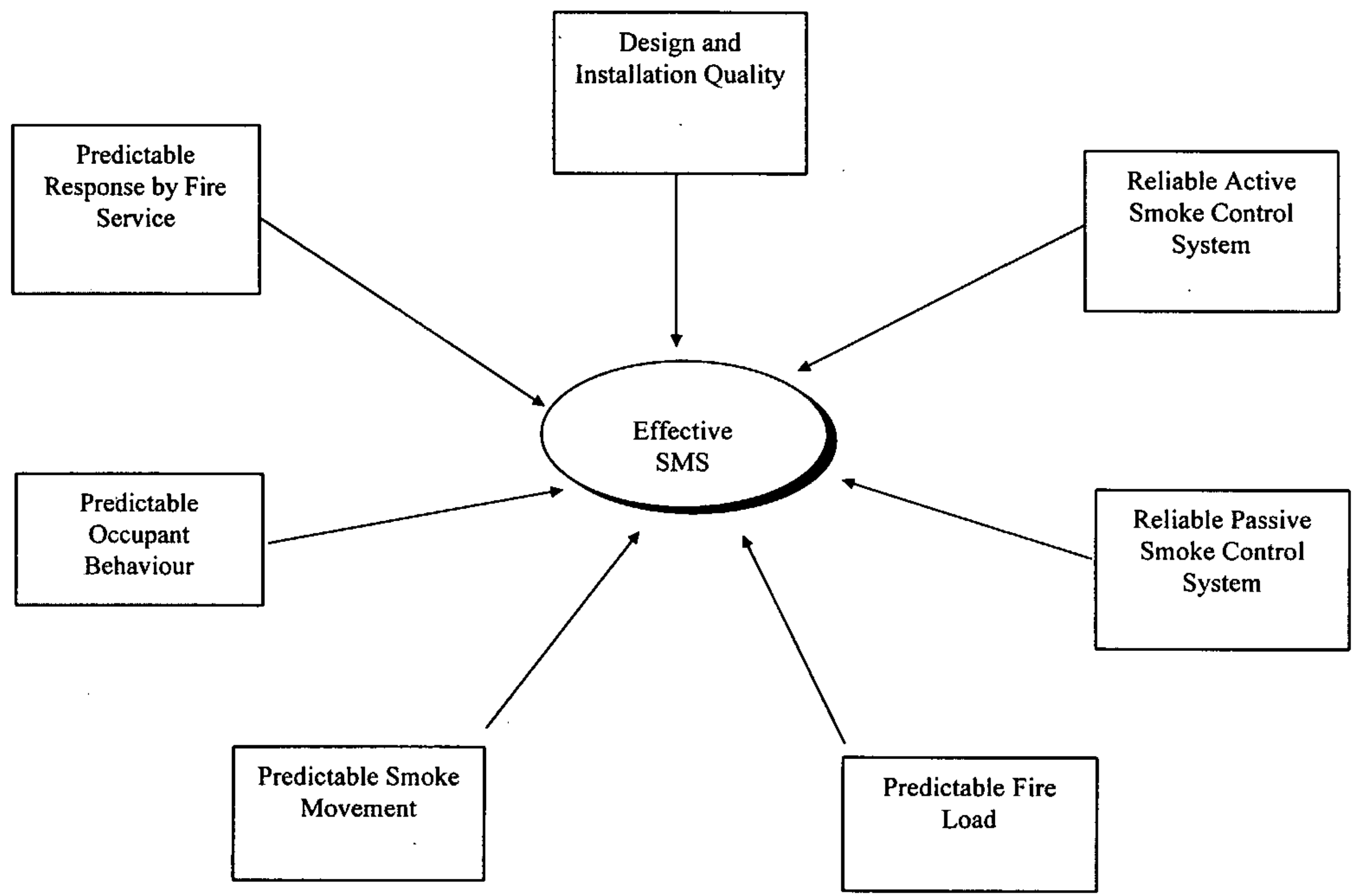


Figure 2 : Network Diagram for Sample Subsystem (after Fitzgerald, 1991)

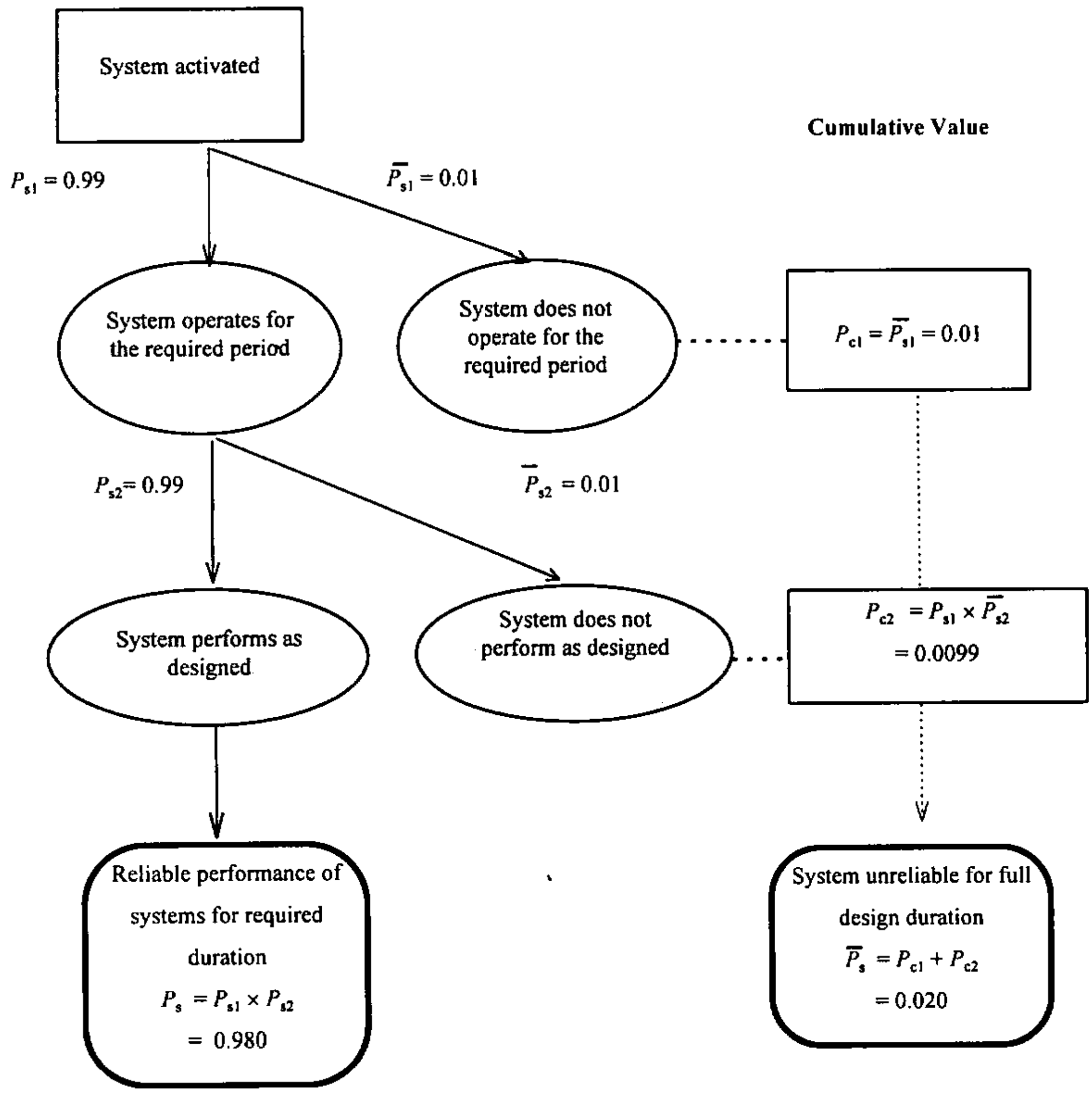


Figure 3 : Diagrammatic Representation of an Electrical Circuit in Series

Figure 4 : Factors Contributing to the Effectiveness of a SMS

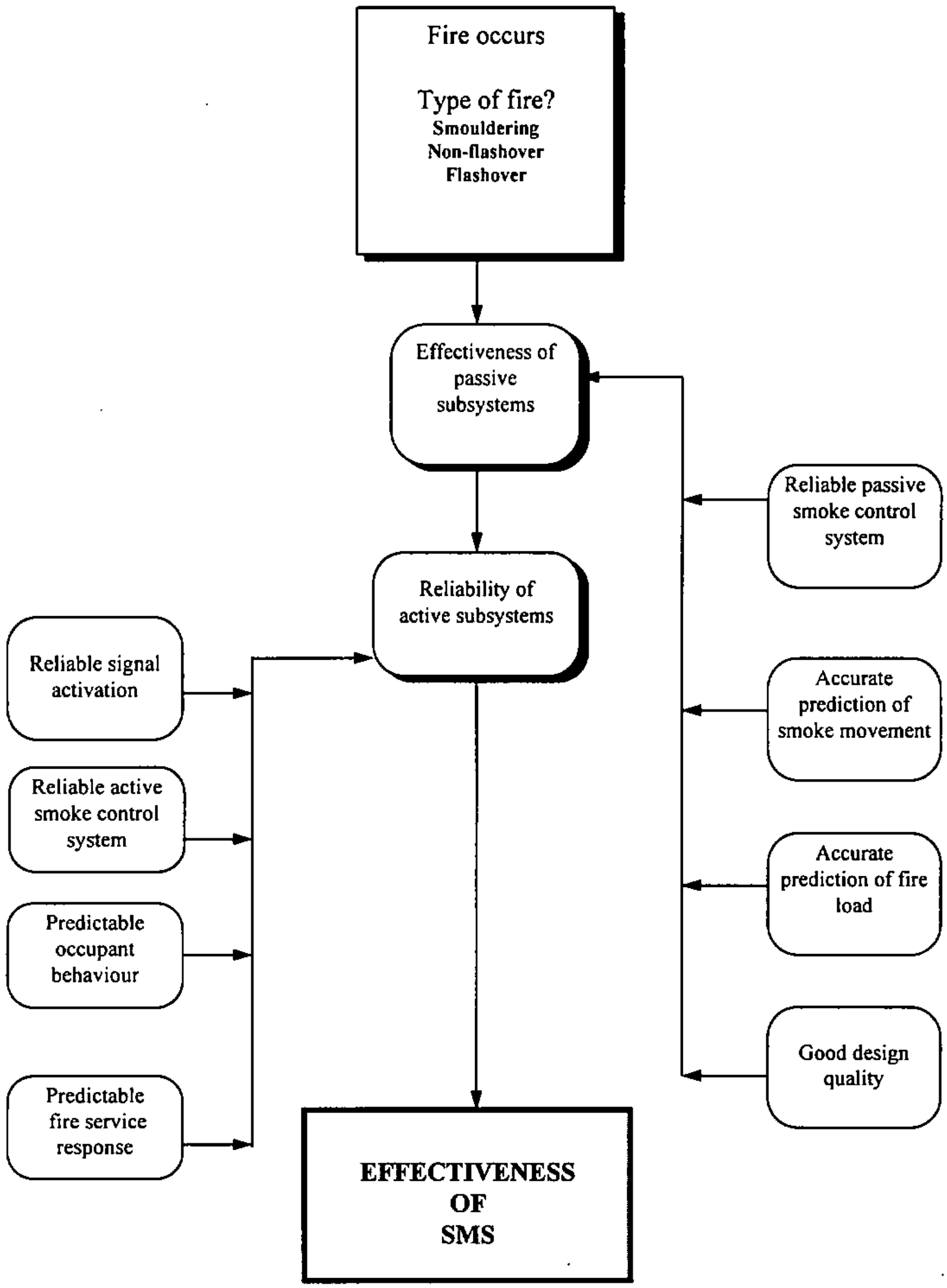


Table 1 : Components in a Reliable Smoke Management System

Main Components	Sub Components
1. **Active Subsystems:**	i. **Signalling System** ii. **Active Smoke Control System:** • Power supply subsystem • Age of components subsystems • Installation subsystem • Commissioning subsystem • Maintenance subsystem • Periodic testing subsystem • New technology subsystem iii. **Occupant Behaviour Subsystem** iv. **Fire Service Subsystem**
2. **Passive Subsystems**	v. **Passive Smoke Control Systems** • Smoke Barriers • Smoke Reservoir • Natural Ventilation vi. **Smoke Movement Subsystem** vii. **Fire Load Subsystem** viii. **Design Quality Subsystem**

3.2 Active Subsystems

3.2.1 Active Smoke Control System (ASCS)

The effectiveness of the active smoke control system subsystems is dependent on the reliability of the following elements:

- Signalling system
- Power supply
- Installation
- Commissioning
- Age
- Periodic testing

- Maintenance
- New Technology

- **Signalling Systems:** On detection of fire or smoke, signalling systems:

    - Automatically indicate the need for evacuation of the building or fire area
    - Protect property through the automatic notification of a responsible person, and
    - Automatically activate fire safety devices.

Heat, smoke and/or electromagnetic radiation (light) is required to activate these signals. Signalling systems require a threshold level of one or all of these characteristics of fire to be activated. Thus the reliability of different signalling systems is affected by the intensity and type of fire experienced. The standards of performance and reliability of such systems are included in NFPA 72 (NFPA, 1993b). Signalling systems include:

- Protected premises fire alarm systems
- Off premises fire alarm systems.

Poor performance of signalling systems will impact adversely on early detection, evacuation and response of fire safety devices. In assessing the reliability of the signalling subsystem the designer is often faced with questions such as:

- Response of detectors (based on the type and make) to different fire scenarios
- Location of detectors, alarms and PA systems, and their effect on early detection and notification of the fire to others in the building.

The network diagram for this subsystem is shown in Figure 5.

- **Power Supply:** The management of a reliable power supply includes the need for:

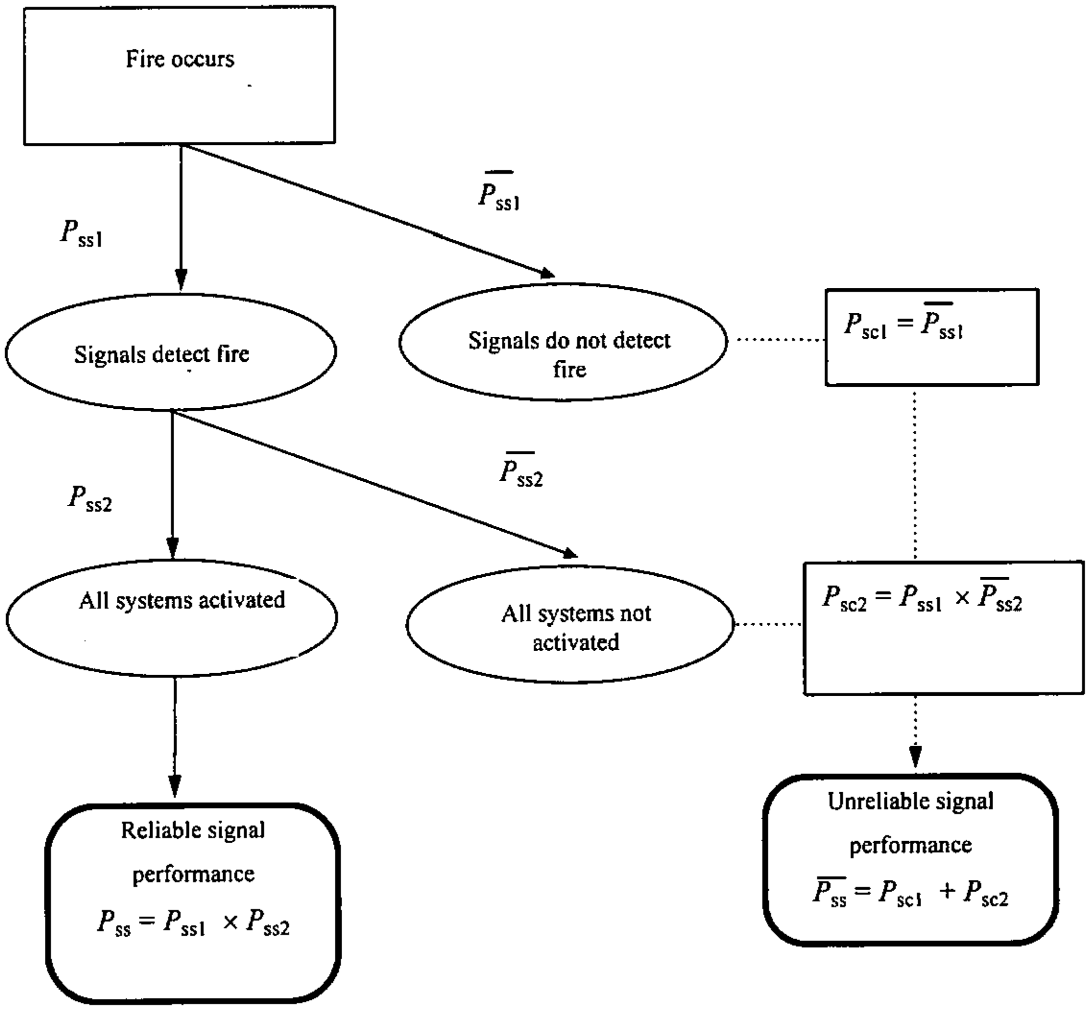
    - An adequate (existing, emergency and backup) power supply which is available to support the active system
    - A power supply that can be maintained for the full duration for which the SMS is required to be effective.

Reliable power supply described in Figure 6 is dependent on (Chapter 32, ASHRAE, 1991):

- System interaction
- Utility rate of power
- Quality of power supply.

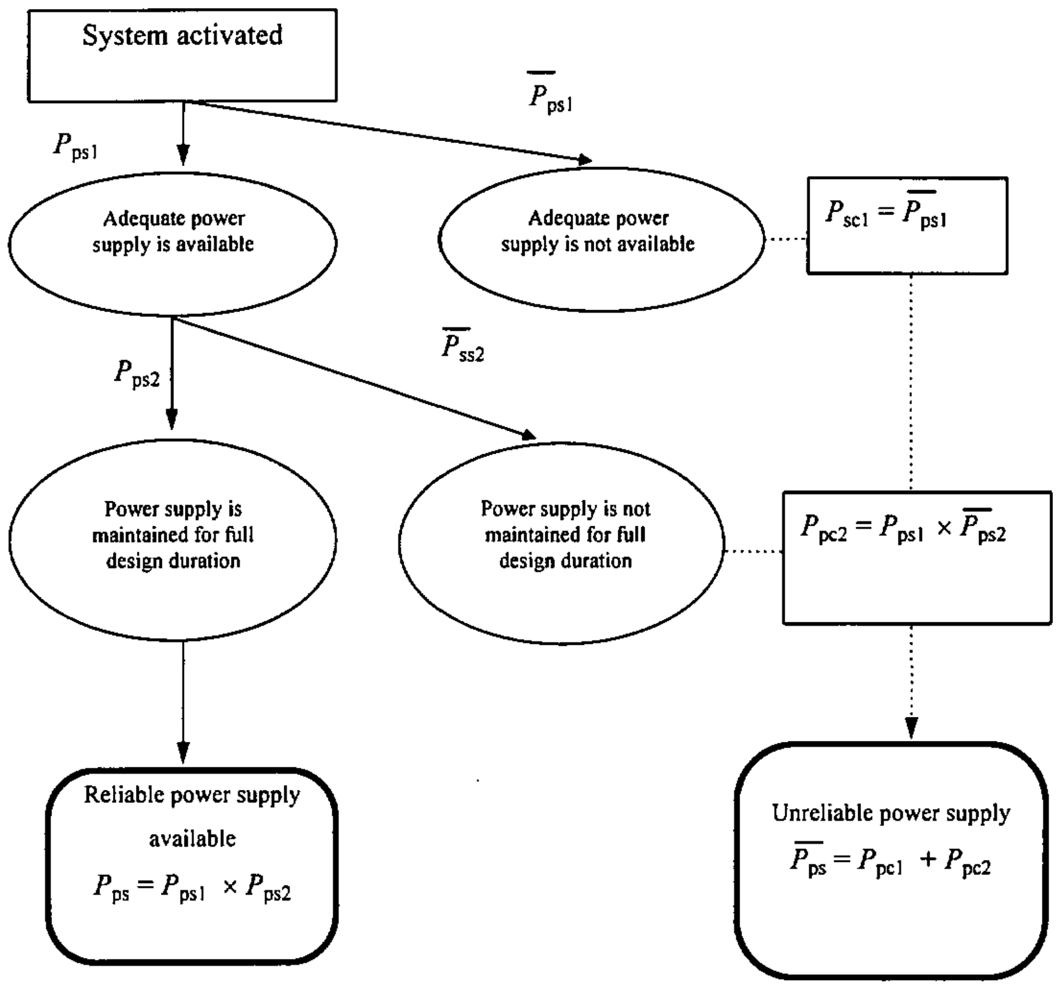
Clear priorities must be set in the process of managing power to ensure that adequate power supplies are available at all times for smoke control systems to function effectively in the emergency mode.

Figure 5 : Network Diagram for Signalling System



See Table 2 for definitions.

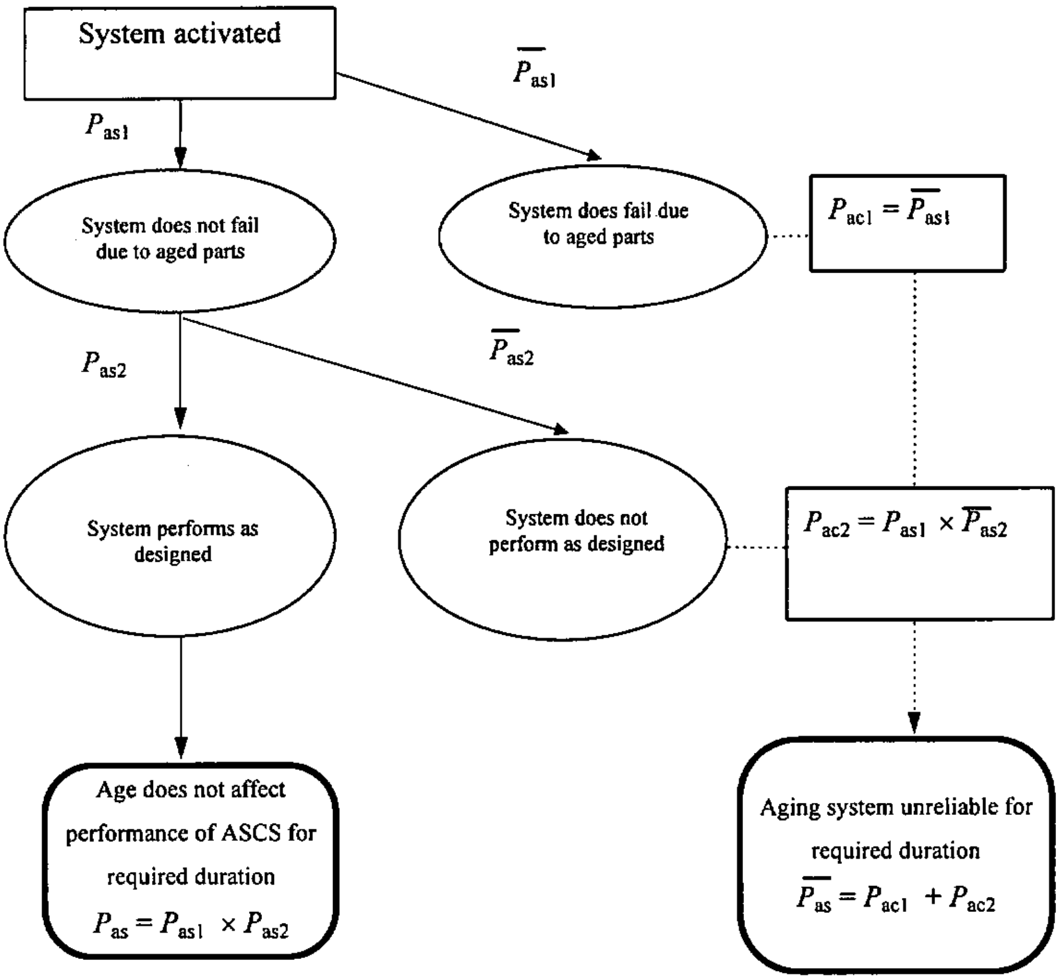
Figure 6 : Network Diagram for Power Supply



See Table 2 for definitions.

- **Age of System Components:** Aging systems are not necessarily prone to more failures. Problems arise when replacement of some elements in the systems may place new and possibly more sophisticated demands on existing subsystems or parts of the subsystem, and where components having limited lives are not replaced. When this occurs there is a tendency for greater strain to be placed on existing components, thus leading to greater potential for failure.

Figure 7 : Network Diagram for Age of System Components



See Table 2 for definitions.

- **Installation:** In many cases failure of the active smoke control systems can be attributed to faulty installation. Generally, the main areas of concern are in the installations of :

  - HVAC ductwork
  - Electrical fitting
  - Restraints against falling debris during emergencies such as fire and earthquakes
  - Back-up power supply, and
  - Detection and signalling systems

Guidelines for correct installations of the components of the smoke control system are provided in various standards or codes. Close adherence to these standards for installations are used as measures for the reliabilities of the elements in this subsystem. Correct installation standards and procedures are based on the following standards:

- Installation of ductwork (BSI, 1989)
- Electrical installations (NFPA, 1993a; SA, 1991)
- Seismic restraint (SNZ, 1983)

- Installation of backup power supplies (SNZ, 1981)
- Installation of signalling systems (NFPA, 1993b).

The reliability of installations is also affected by the qualification and experience of the installer.

- **Commissioning:** Commissioning of smoke control systems must be carried out to assess the effectiveness of the systems and their ability to provide the protection intended.

The two phase process of commissioning (Klote and Fothergill, 1983) includes:

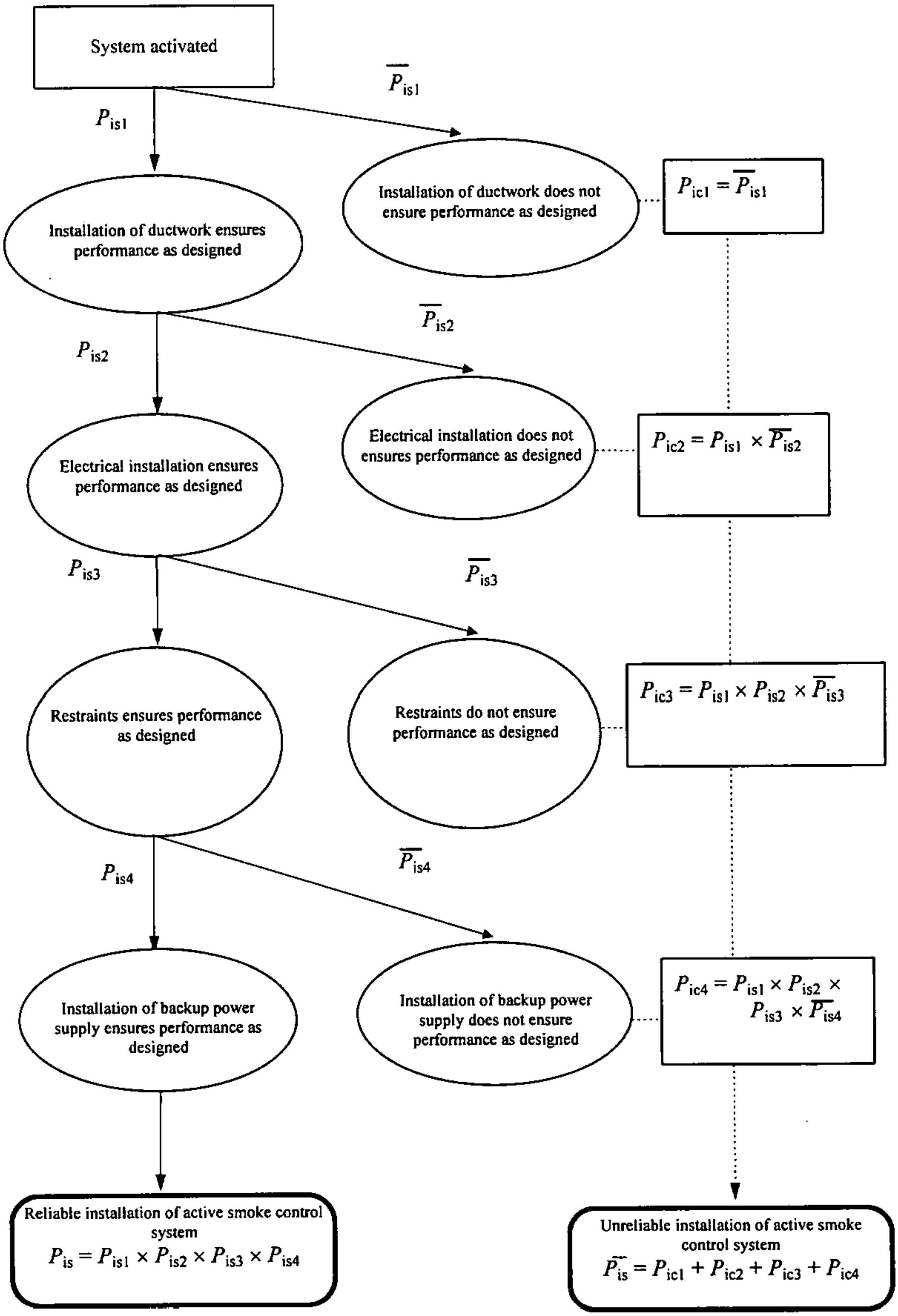
- Testing of individual components to determine their functional performance to specification
- Testing of the smoke control system for the whole or parts of the building to determine the effectiveness of components when working as a system.

This double phase in-situ testing ensures that successfully operating individual components can also effectively function as a system. Testing of smoke control systems in a building is conducted using heated (hot) or unheated (cold) chemical smoke or tracer gases. Guidelines for testing smoke control systems in New Zealand are set in the appropriate standards such as NZS 4238 (SNZ, 1991), or AS1668.1 (SA, 1991) and are in general agreement with the two phase testing as discussed above. The following aspects are monitored for both normal and emergency mode operations:

- Flow rate across barriers
- Flow rate at make-up air
- Flow rate at exhaust equipment.

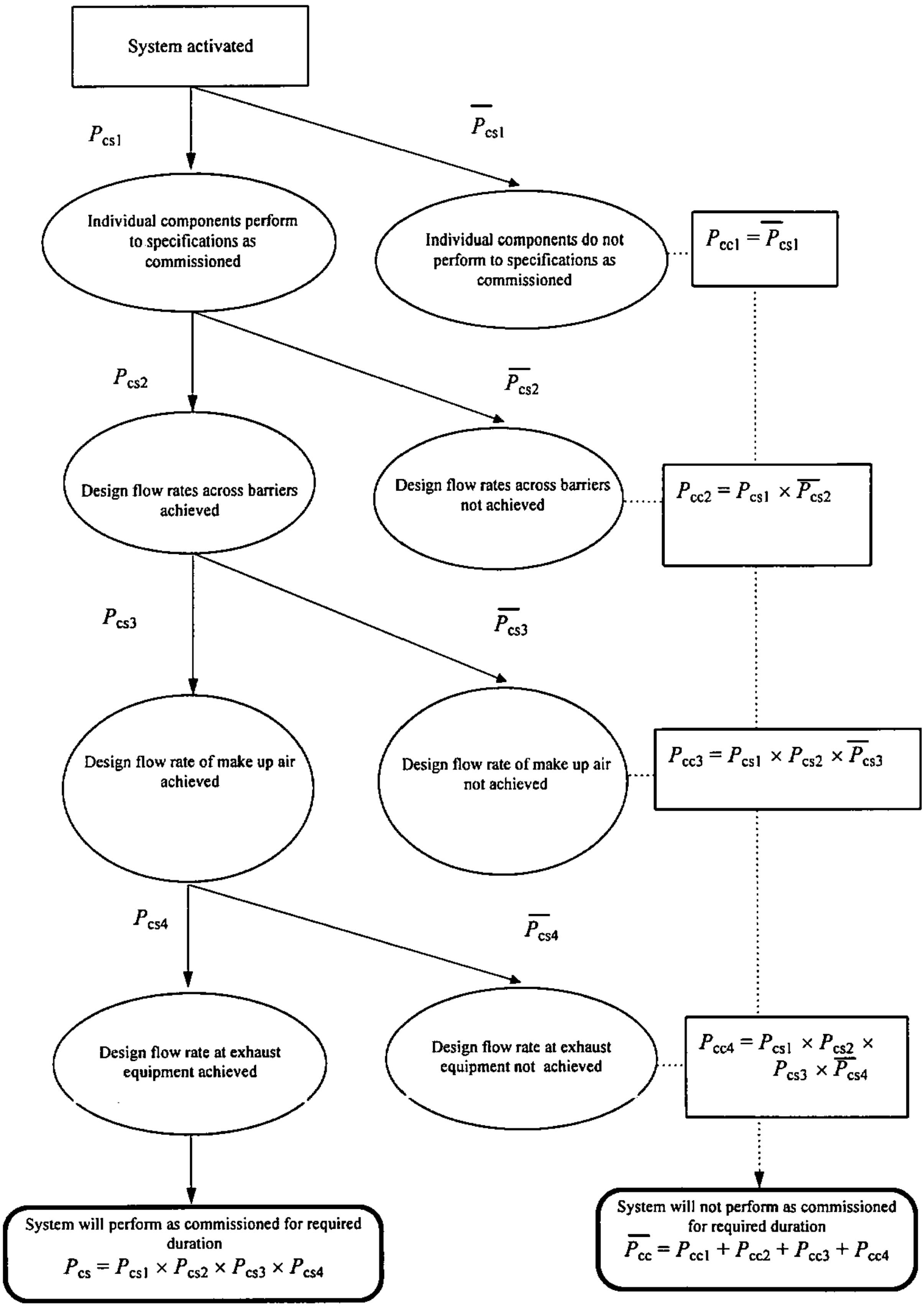
Correctly commissioned smoke control systems have better likelihood of achieving the design objectives. A standard for the commissioning of smoke management systems is currently being developed by ASHRAE (Klote, 1992).

Figure 8 : Network Diagram for Installation of System Components



See Table 2 for definitions.

Figure 9 : Network Diagram for Commissioning of ASCS



See Table 2 for definitions.

- **Maintenance:** Poor maintenance has been often cited as one of the major reasons for the ineffective performance of smoke management systems during emergencies. Good maintenance will improve reliability. The whole concept of maintenance is based on two objectives:

    - Prompt response to mechanical failure
    - Periodic attention to equipment and process through planned and preventive maintenance.

These objectives are met through:

- Effective coordination between the design engineers, manufacturers, contractors and building owners or managers
- Development of an effective maintenance program and manuals
- Maintenance of equipment.

Non-dedicated smoke control systems are more likely to have faults detected during normal operations in comparison with dedicated systems that are activated only during an emergency. In either case poor maintenance will directly affect the performance of the smoke management system.

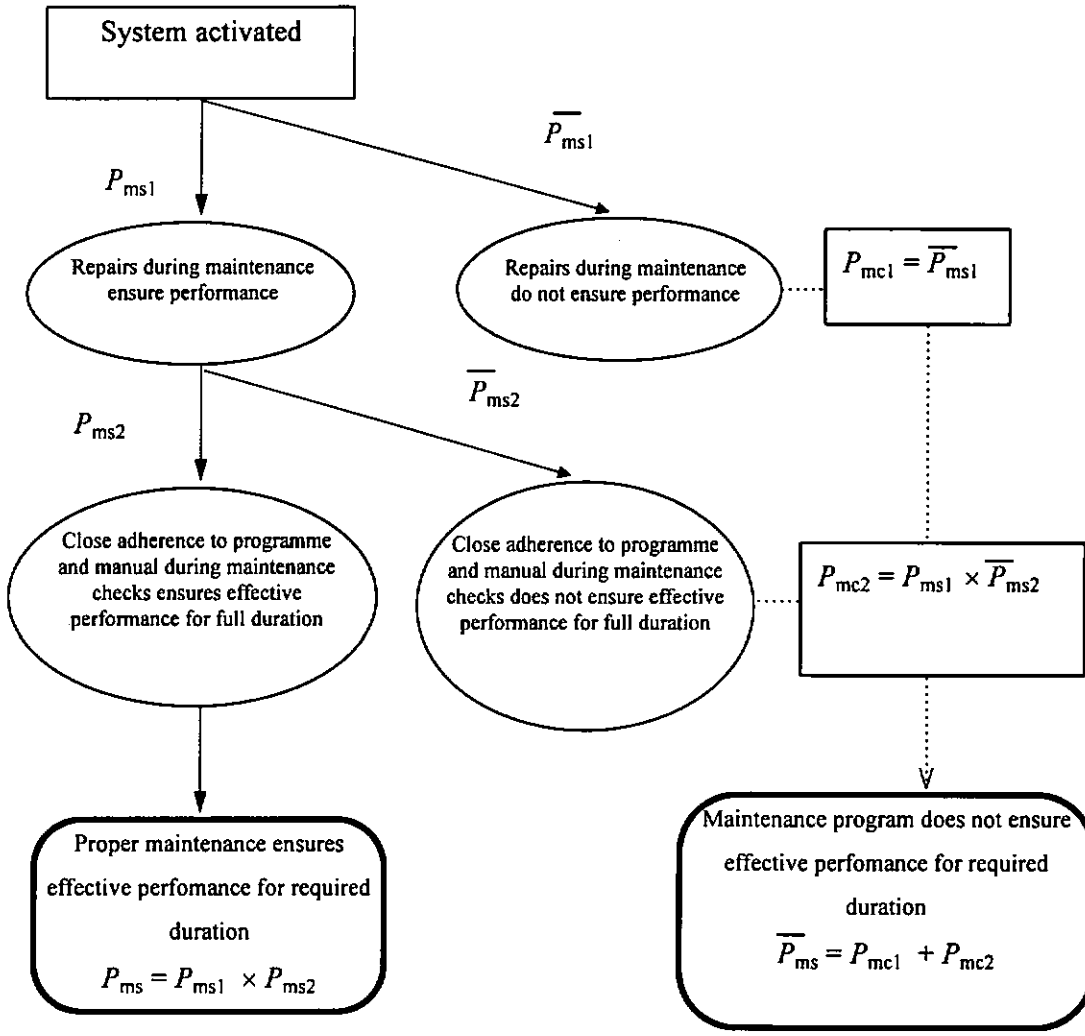
- **Periodic Testing:** Commissioning ensures that smoke management systems will perform as designed during an emergency. Correct performance at the time of commissioning of a new system does not ensure that the system will perform effectively during an emergency. Thus regular testing is required to provide confidence that the system will perform as designed. Periodic testing complements activities that will be carried out during maintenance and commissioning.

- **Technology:** New technology (Chapter 35 and 36 of the ASHRAE Handbook, ASHRAE, 1991) is available in the form of:

    - Electronic control devices
    - Digital processing
    - Computer applications, and
    - Electronic communication process and devices.

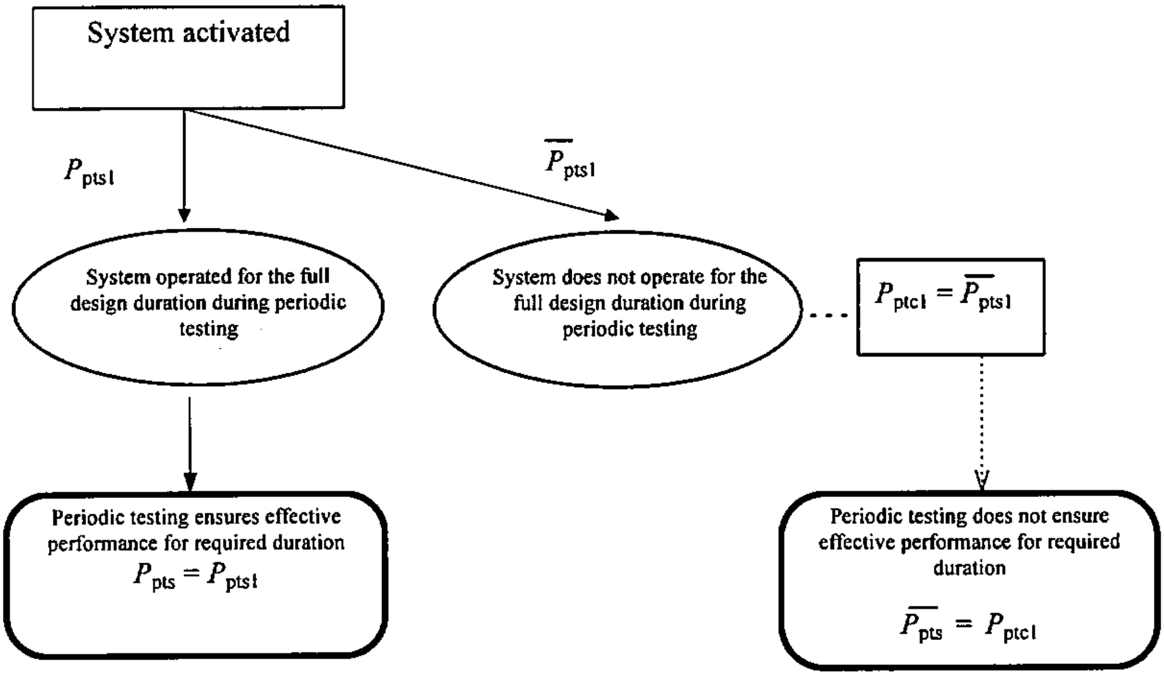
Knowledge-based or expert systems are currently being applied in the industry to improve the reliability and performance of individual components of the SMS. These systems have the ability to replicate human decision-making processes in the operation and maintenance of smoke management systems. Operations and maintenance programs developed during the design and implementation of the smoke management system must be closely adhered to throughout the service life of the facility or the system (ASHRAE, 1991). A comprehensive study of the effect of new technology on the operation and maintenance must be undertaken before any changes are made. Failure resulting from incompatible technology is often picked up during commissioning, periodic testing and maintenance.

Figure 10 : Network Diagram for Maintenance



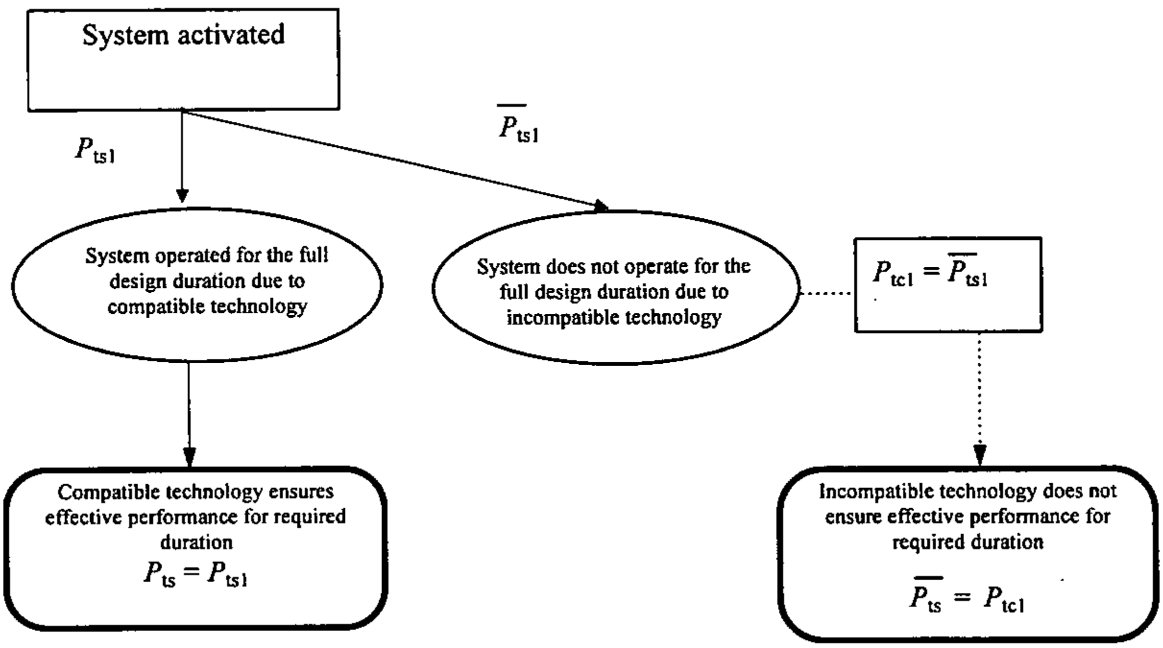
See Table 2 for definitions.

Figure 11 : Network Diagram for Periodic Testing



See Table 2 for definitions.

Figure 12 : Network Diagram for Technology



See Table 2 for definitions.

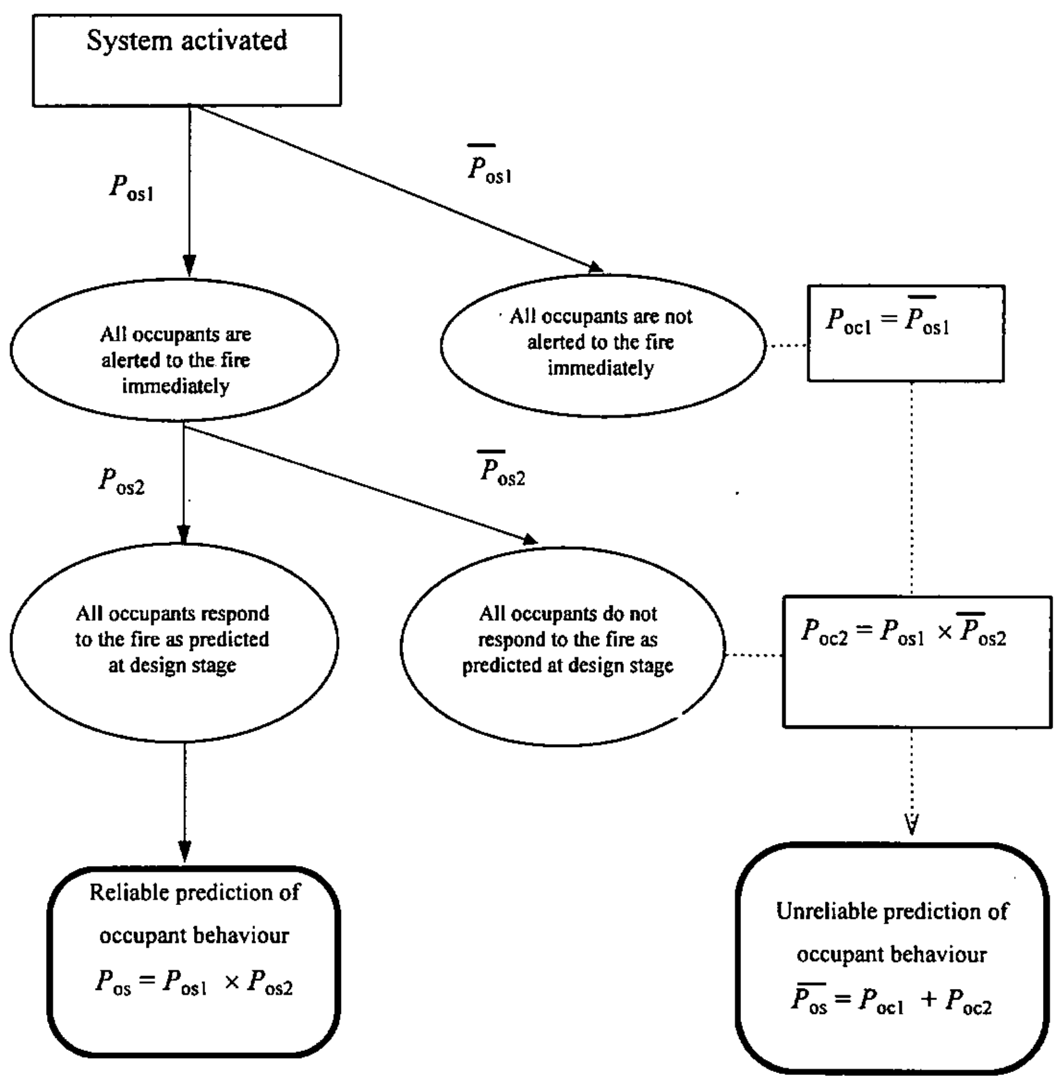
3.3 Occupant Behaviour

Traditionally SMS designs have been based on occupants following a particular pattern of behaviour during emergency evacuation. Current research findings (Proulx, 1995) show that using static models for occupant behaviour is misleading in regard to what occupants actually do during emergency evacuation, and does not closely map what happens in reality. Thus the accuracy with which occupant behaviour can be predicted will impact greatly on reliability of the SMS.

Observations made during evacuation trials in Canada (Proulx, 1995) clearly indicate that occupant response models adopted at the design stage vary significantly in practice. This gap between design and site observations has been attributed to:

- General change in occupant behaviour with time
- Changes in occupancy
- Design based on an inadequate understanding of human behaviour.

Figure 13 : Network Diagram for Occupant Behaviour



See Table 2 for definitions.

3.4 Fire Service

One of the objectives in the design of smoke management systems is to provide a tenable environment for trained firefighting personnel to conduct their search and rescue, and fire suppression activities within the building during a fire.

Traditional designs have generally tended to exclude the impact of the Fire Service on the overall performance of the SMS. The response times of the Fire Service and the strict adherence to firefighting procedures will impact significantly on the reliability of the SMS in being able to provide a tenable environment for firefighters to carry out their operations. Thus, within the scope of this project, the contribution of the Fire Service is considered as part of the SMS. The following activities by the Fire Service will affect the SMS:

- How quickly the Fire Service is notified and their response times
- Procedures in venting to allow additional smoke extraction
- The closeness with which procedures are adhered to.

The duration for which the SMS can continue to perform this function effectively will depend directly on the operating temperatures and the volume of smoke. It can be expected that the effectiveness of the SMS will drop significantly during the later stages of the fire, when higher temperatures and greater volume of smoke generation may be experienced. The duration for which the SMS must provide this service will depend on:

- How soon the Fire Service can get to the scene of the fire
- How closely the firefighting personnel adhere to the fire suppression strategies as assumed at the design stage of the SMS.

Thus the reliability of the Fire Service response time and their strict adherence to procedures as assumed at design phase will affect the overall effectiveness and performance of the SMS. Recent studies (Narayanan and Whiting, 1996) indicate that the New Zealand Fire Service responds to 85% of all structure fires within 8 minutes.

3.5 Passive Subsystems

3.5.1 Passive Smoke Control Systems (PSCS)

Resistance and containment of hot gases is the primary consideration for the effectiveness of passive smoke control systems. Passive smoke control systems such as smoke barriers, smoke reservoirs and natural ventilation form built-in features of the building that are functional at all times (Narayanan, 1993). They serve one or both of the following purposes during a fire:

- Restricting the spread of smoke and fire by forming barriers or restricting ventilation
- Restricting the passage of smoke to areas away from escape routes.

The importance of passive systems lies in their ability to restrict the spread of smoke during the early stages of a fire (pre-flashover) when occupants are evacuating the building. Better smoke control performance can also be obtained in the later stages of the fire (post-flashover stages) from the use of fire-resistant building elements (Narayanan, 1993).

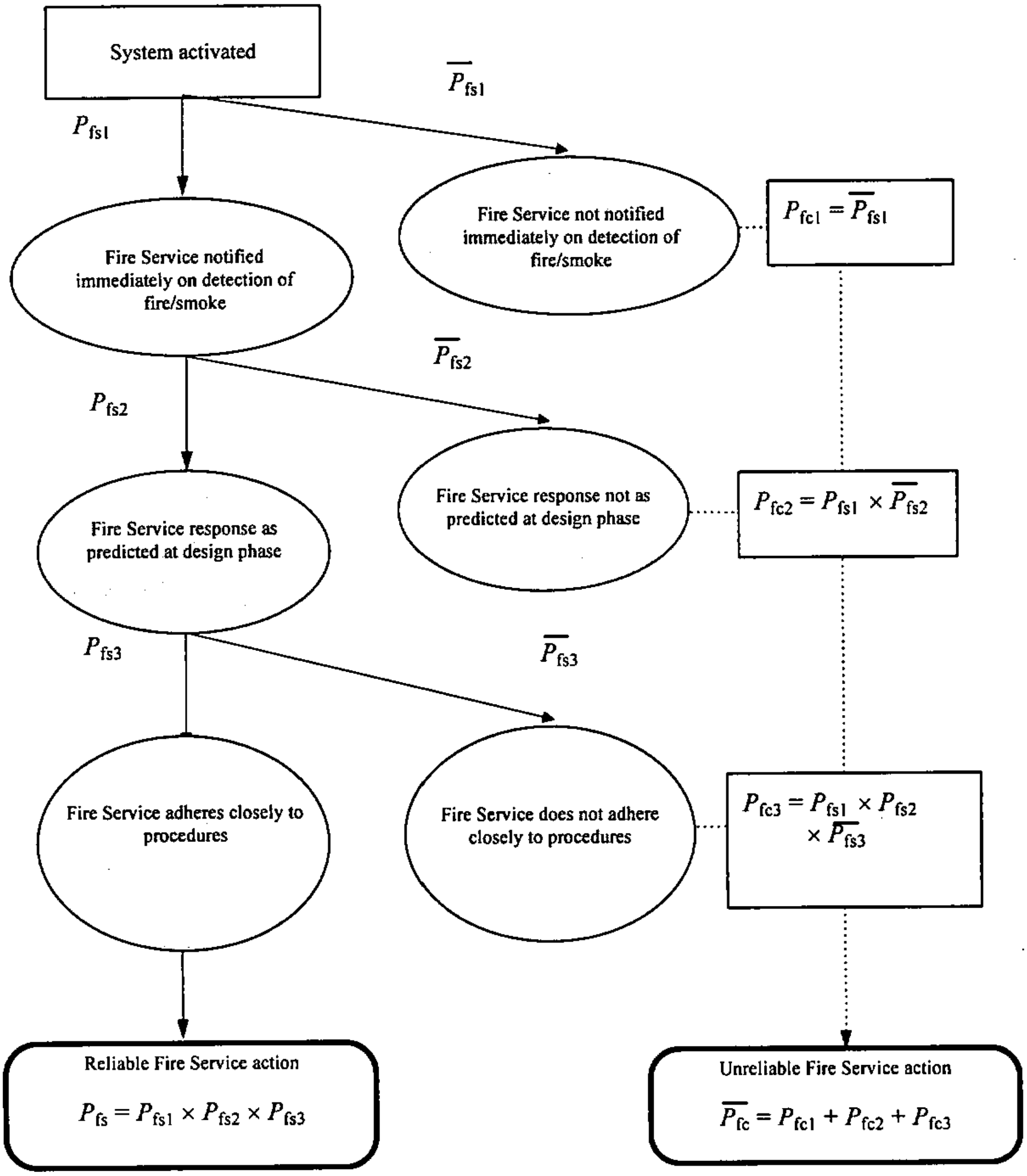
Effective performance of passive smoke control systems is founded on their ability to maintain integrity for the duration and intensity of the fire. Real fire temperatures may vary greatly from the standard time-temperature curves (SA, 1990) used in testing the fire-resisting performance of construction elements. However, it may be expected of elements that satisfy the above standard test that integrity failure will not occur in the early stages of a fire in a firecell. Satisfactory fire resistance and effective design and location of these systems are important for their useful functioning. Their design and locations are based on fire and smoke control strategies for each individual building (Narayanan, 1993).

Smoke Barriers: Imperforate floors, ceilings and walls form adequate smoke barriers. Smoke leakage problems arise when there are penetrations or construction joints in these elements (Narayanan, 1993). All gaps between penetrations and smoke separations must be impermeable to smoke, including all seismic gaps and service duct penetrations that may be provided in floors, ceiling and walls. Gap seals complying with AS 1530.4 (SA, 1990) or with BS 476 Part 24 (BSI, 1987), where the fire-resisting performance of sealed gaps is tested as part of the ductwork, are accepted as suitable for building construction in New Zealand.

Smoke Reservoirs: Uncontrolled horizontal smoke spread can cause loss of buoyancy due to cooling of the smoke layer. This may lead to increased downward mixing. There is also a tendency for cool smoke to stagnate, often rendering distant vents ineffective. In buildings with large undivided floor areas, smoke reservoirs restrict horizontal spread of smoke. The design volume that the reservoir is required to retain at any one time is based on the mass flow rate of smoke entering the reservoir (Narayanan, 1993).

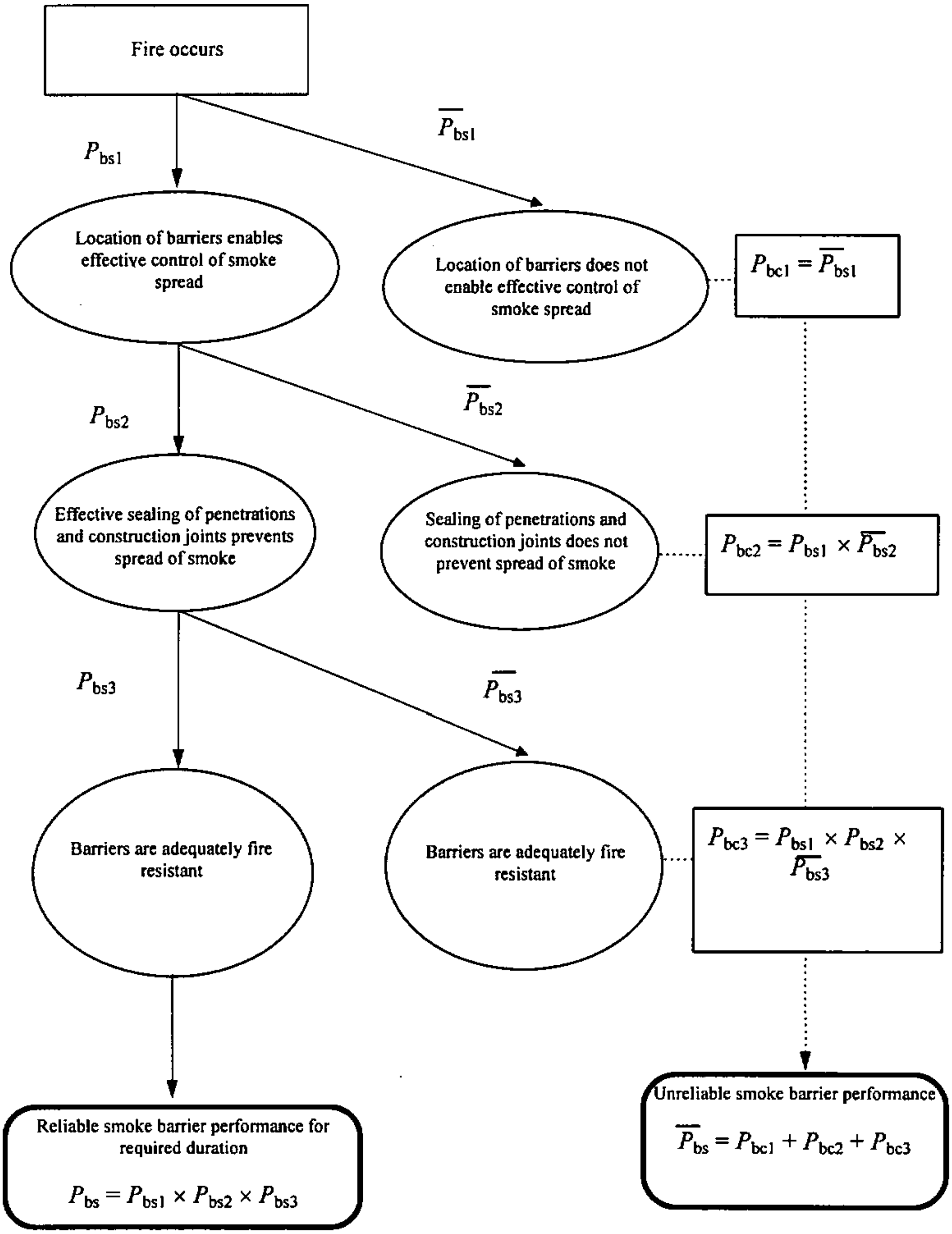
Natural Ventilation: Smoke extraction by natural ventilation may be used independently or in combination with mechanical extraction. Mechanical methods may be required when wind conditions are not favourable for natural ventilation. Extraction rates are affected by pressures developed just outside the vents by wind or air movement on the exterior of the building. Thus the reliability of such subsystems relies on the effective design and location of vents.

Figure 14 : Network Diagram for Fire Service Action



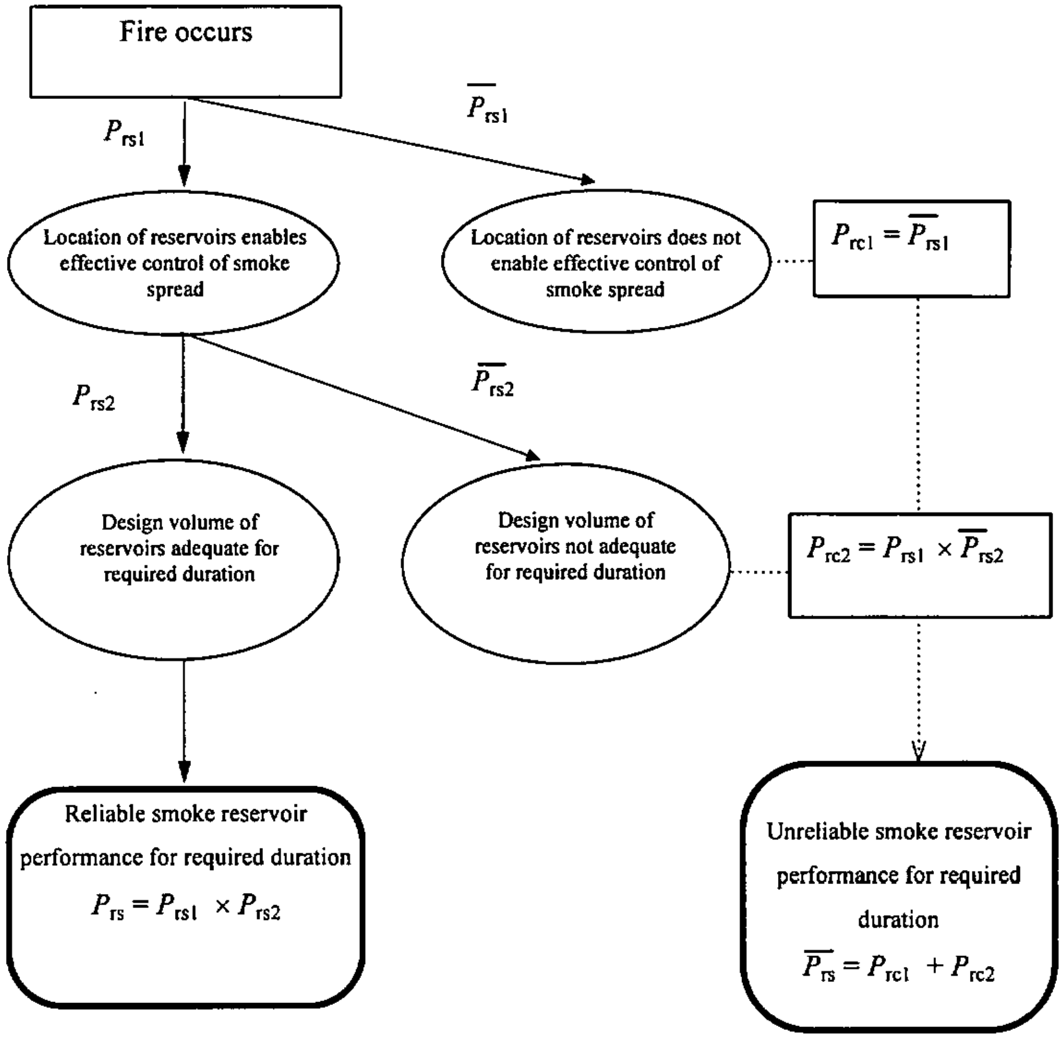
See Table 2 for definitions.

Figure 15 : Network Diagram for Smoke Barriers



See Table 2 for definitions.

Figure 16 : Network Diagram For Smoke Reservoirs



See Table 2 for definitions.

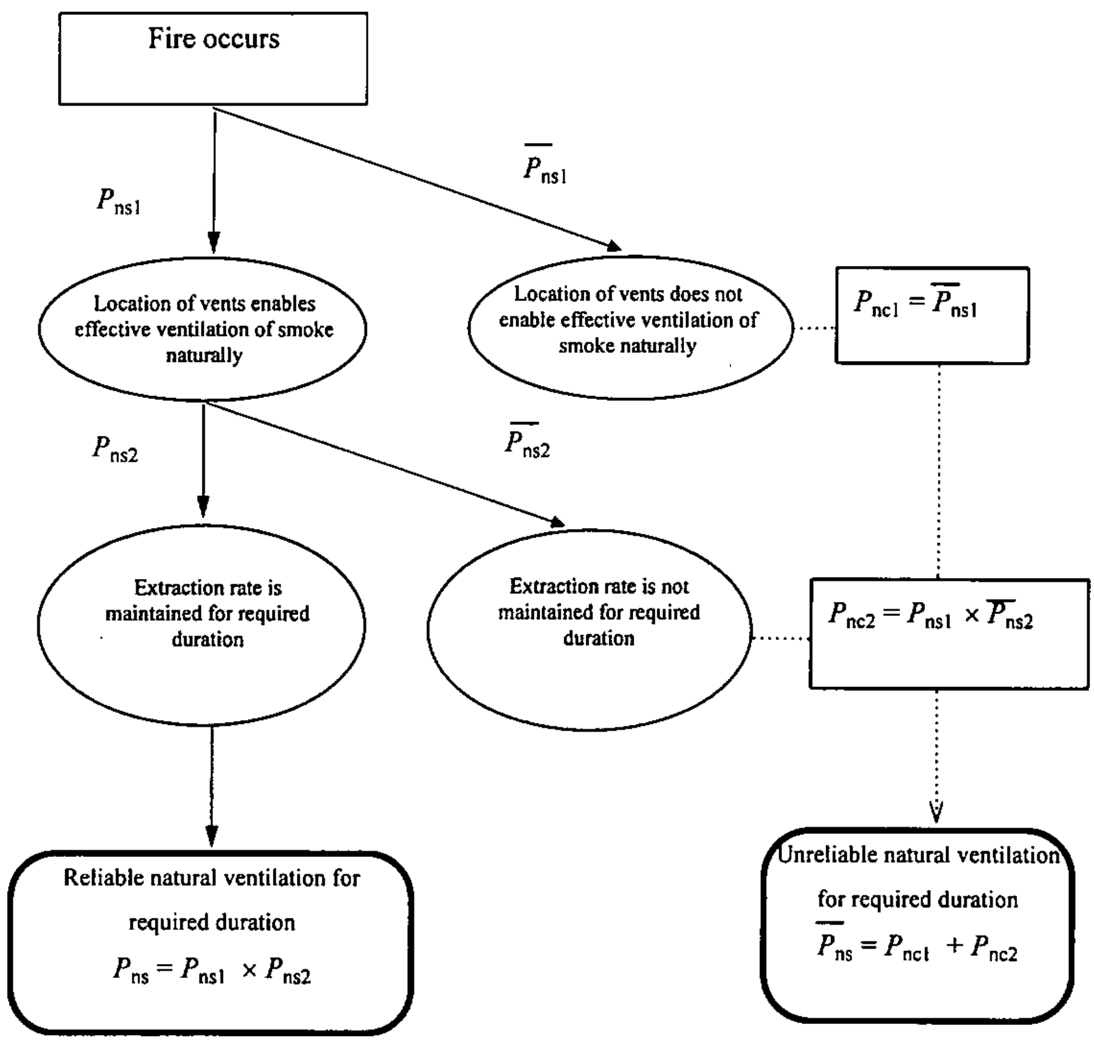
3.6 Movement of Smoke

The movement of smoke in a building is largely influenced by the effects of the fire, wind and stack pressures.

Fire Effect: In the early stages of a fire there is a rapid increase in the temperature in the fire compartment. Air just above the fire in the compartment expands, developing a pressure differential with adjacent spaces. This causes smoke to spread through horizontal and vertical openings to cooler parts and adjacent spaces. In a fully developed compartment fire with smoke temperatures of 1000°C and the neutral axis at 1.0 m above the ground level, the increase in pressure at a door head 2.0 m above the floor is about 5 Pa (Butcher and Parnell, 1979). This small pressure differential is sufficient to transport smoke to adjacent spaces. All other factors remaining constant, in a steady-state situation the effect of buoyancy diminishes due to heat loss and dilution as smoke moves further away from the fire, and as the temperature in the fire compartment stabilises.

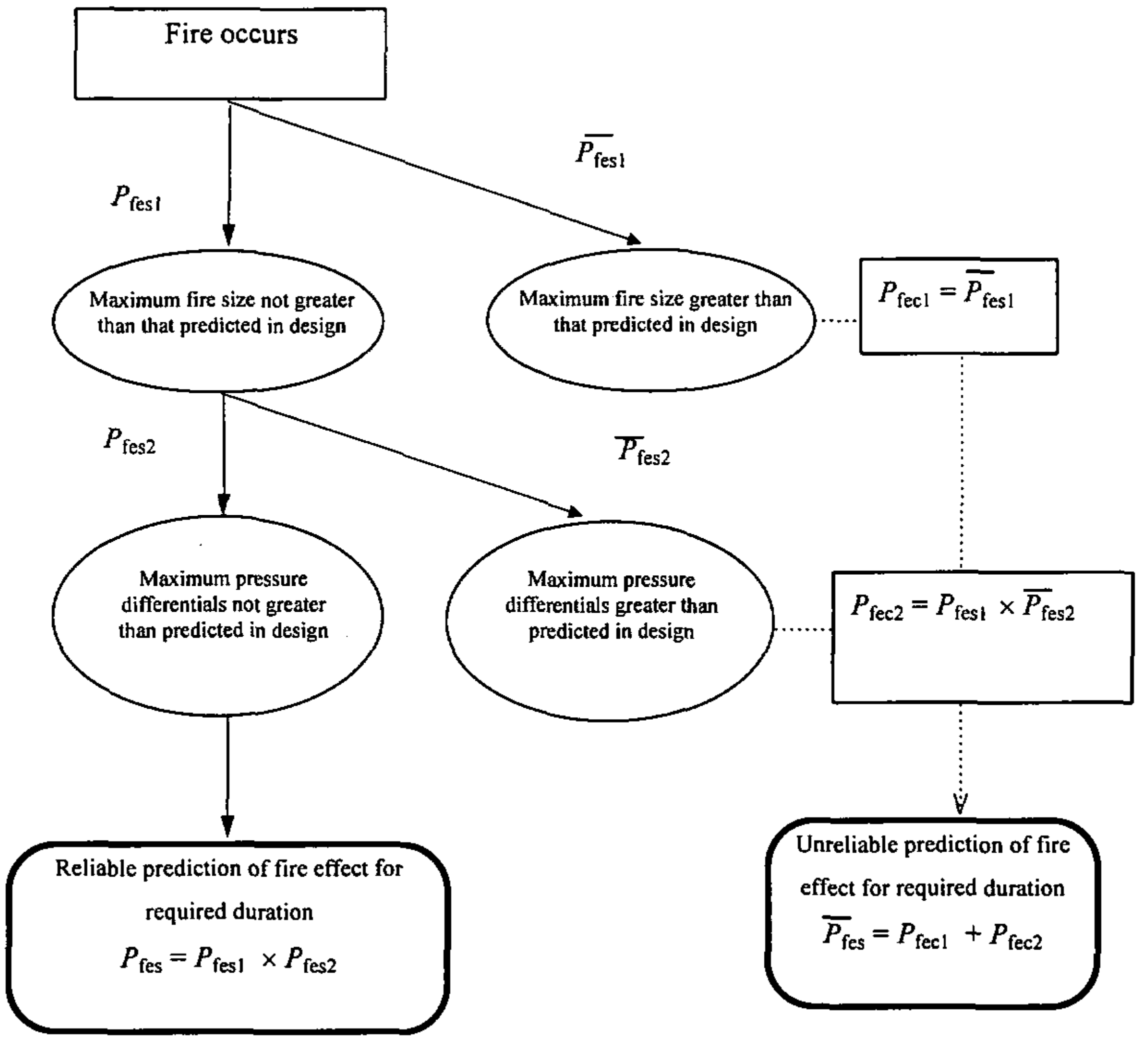
The effect of thermal expansion is therefore more pronounced in smaller buildings such as residential dwellings compared to high rise buildings where its influence is significant only in the very early stages of a fire. Thus the reliability with which the fire size can be predicted at the design stage based on the fire load will affect the effectiveness of the overall smoke management system.

Figure 17 : Network Diagram for Natural Ventilation



See Table 2 for definitions.

Figure 18 : Network Diagram for Fire Effect

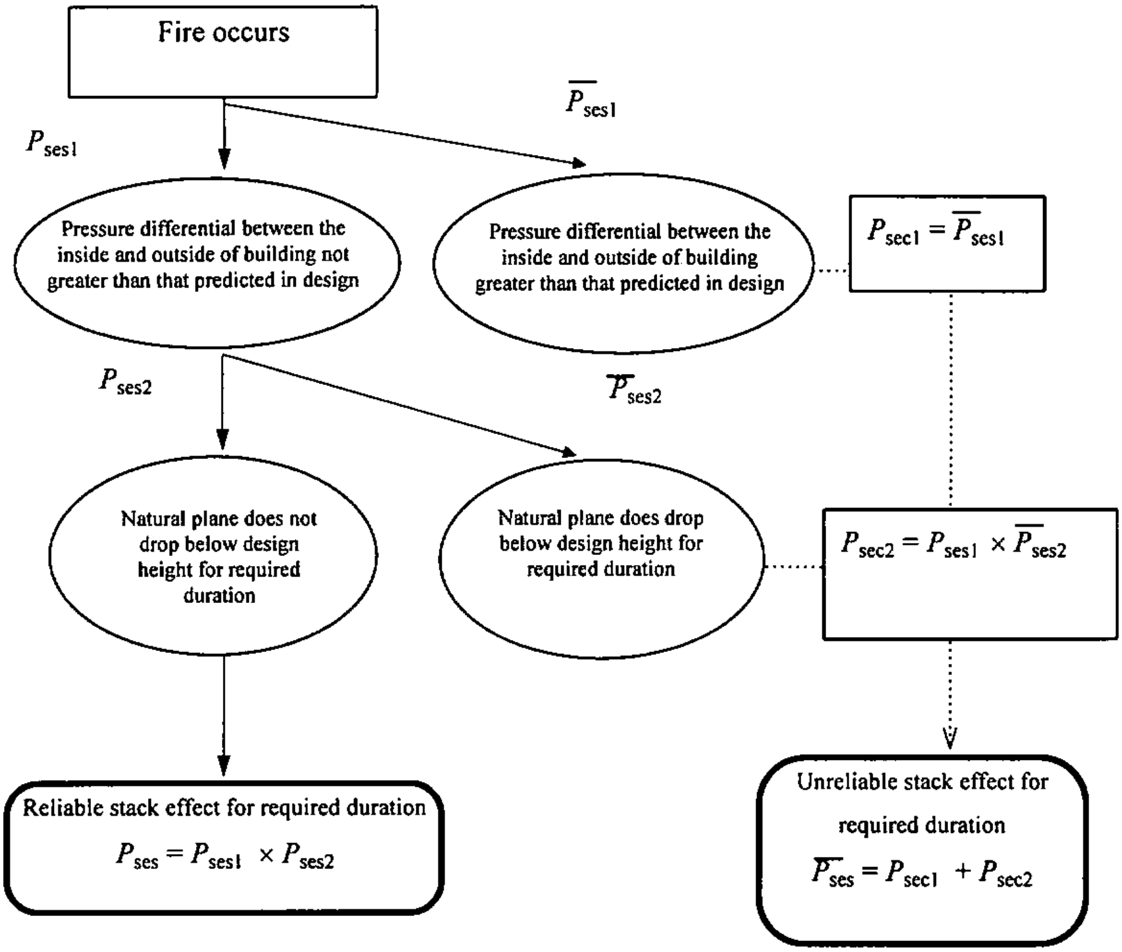


See Table 2 for definitions.

Stack Effect: Stack effect is caused by the difference in temperature between the interior and exterior of a building. During a fire, smoke and hot gases may spread to places very remote from the fire compartment due to this phenomenon. Normal stack effect exists when the exterior is cooler than the inside of a building. This causes dense cool air from the outside to flow into lower floors of the building and displace the lighter but warmer air in the building to the upper floors. This gives rise to a pressure differential between the interior and the exterior of the building. The height of the neutral plane is generally affected by the air handling and ventilation systems and local floor temperatures in the building. Reverse stack effect exists when the interior of the building is cooler than the exterior.

The reliability with which stack effect can be predicted will affect the design of the smoke management system and will therefore affect the overall reliability and effectiveness.

Figure 19 : Network Diagram for Stack Effect

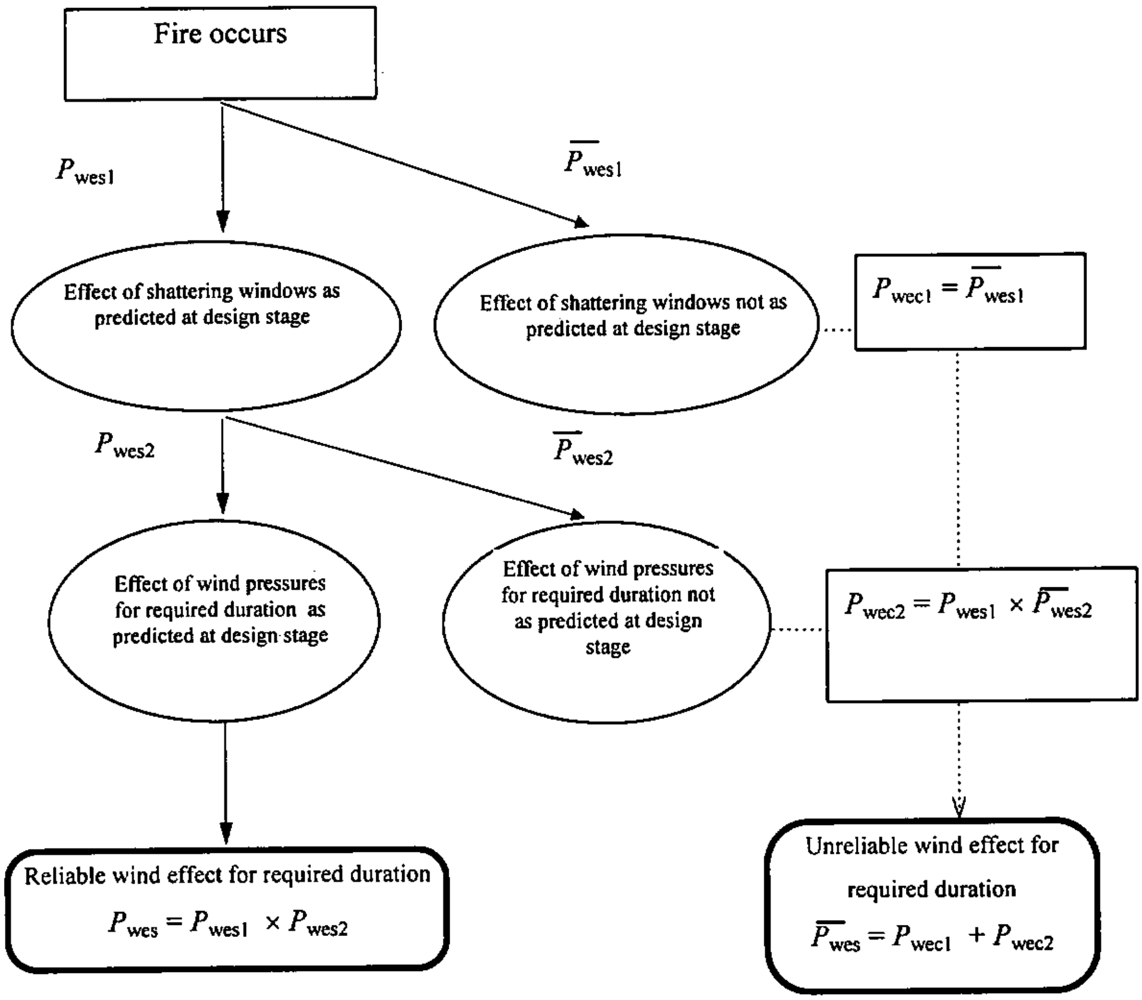


See Table 2 for definitions.

Wind Effect: The effect of wind on air movement within buildings is significant. Temperatures in fire compartments are often sufficient to shatter glass panels and windows at an early stage. Shattered windows on the leeward side of the fire floor help vent smoke and curtail smoke logging within the building. On the windward side, broken windows allow smoke on the fire floor to be pushed into adjacent spaces on that and other floors. Wind pressures on the exterior walls depend on the size and shape of the building and other buildings surrounding it (SNZ, 1992).

Extraction rates are affected by pressures developed just outside the vents by wind or air movement on the exterior of the building. Thus the failure or poor performance of such systems must be considered to impact on the overall performance of smoke control systems.

Figure 20 : Network Diagram for Wind Effect Subsystem

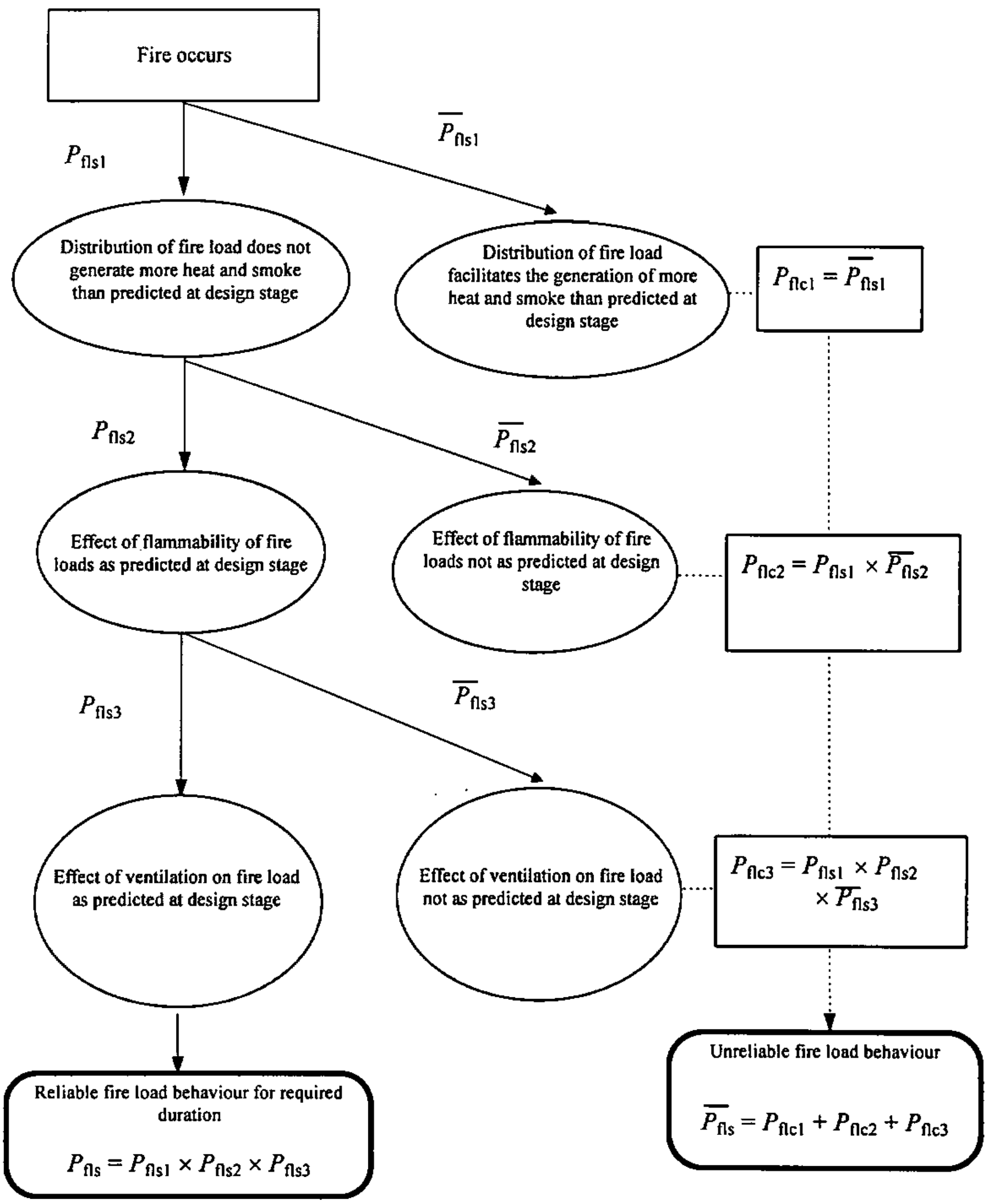


See Table 2 for definitions.

3.7 Fire Loads

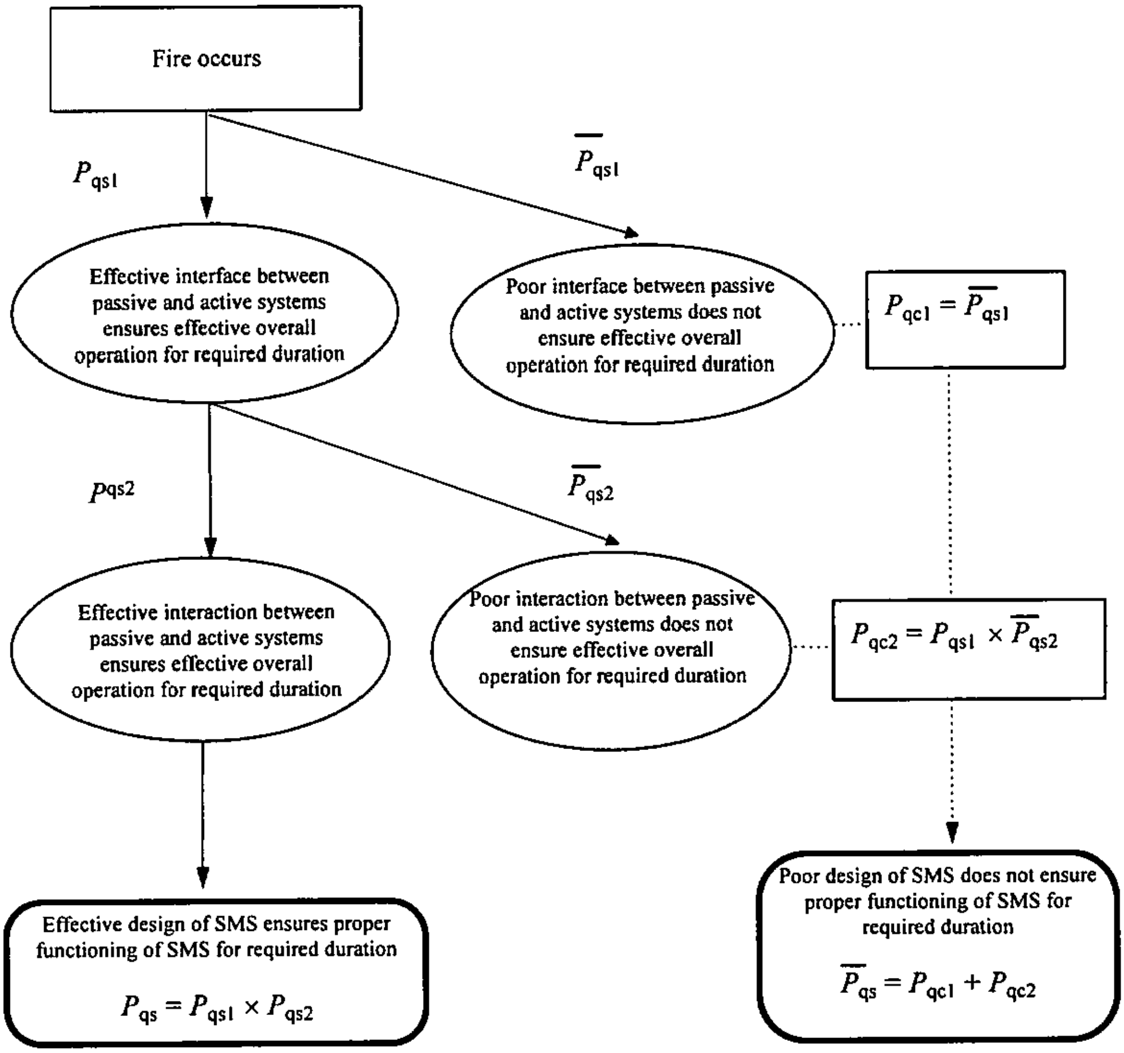
Fire load density varies greatly with building occupancies. Other factors remaining constant, larger fire loads lead to more severe fires in terms of duration. The peak temperatures reached by such fires are governed by the availability of air (ventilation) and the rate of combustion. Thus an accurate prediction of the possible distribution and flammability of the fire load in a firecell will assist the designer to better estimate the likely fire severity and thus provide adequate and cost-effective fire protection (Narayanan, 1995).

Figure 21 : Network Diagram for Fire Load



See Table 2 for definitions.

Figure 22 : Network Diagram for Design Quality



See Table 2 for definitions.

3.8 Design Quality

The quality of design of SMS relies primarily on the skills, awareness and training of the designers.

The performance-based environment of the NZBC (BIA, 1992) allows alternative design solutions for SMS using fire engineering principles. Thus, the experience and knowledge of the designers must be factored in to the measurement of the reliability of the SMS.

Simplicity: As the system gets more complex there is a greater tendency for problems in areas such as installation, testing and interfacing between subsystems. Thus, as systems get more complex, it can be expected that reliability will be adversely affected. SMS designs with simple interfaces will significantly improve reliability of repairs, maintenance and operations. This criteria for measurement of simplicity is based on the requirements of NFPA 92B (NFPA, 1991).

Coordination: A major consideration during design must be the effective coordination and interaction of passive and active subsystems to facilitate balanced operation of the SMS. Poor interface and interlocking of passive and active control systems with other subsystems often leads to super efficient or inadequate systems.

4. COMPUTER MODELLING

4.1 Framework for Computer Model

The computer model is developed as a mixed system. The schematic flowchart showing the assembly of subsystems and their components is shown in Figure 23. The checklist method adopted in this model requires the user to assign reliability levels for each aspect of the SMS. Probability values shown in Table 2 have been used in the computer program. Allowance for modifications by the user has also been made.

4.2 Assumptions

Two assumptions have been made to facilitate the modelling of the SMS :

- The probability of fire occurring = 1.000; and
- Sprinkler action has no effect on the fire or smoke spread.

Figure 23 : Schematic Flowchart for Computer Model Assembly

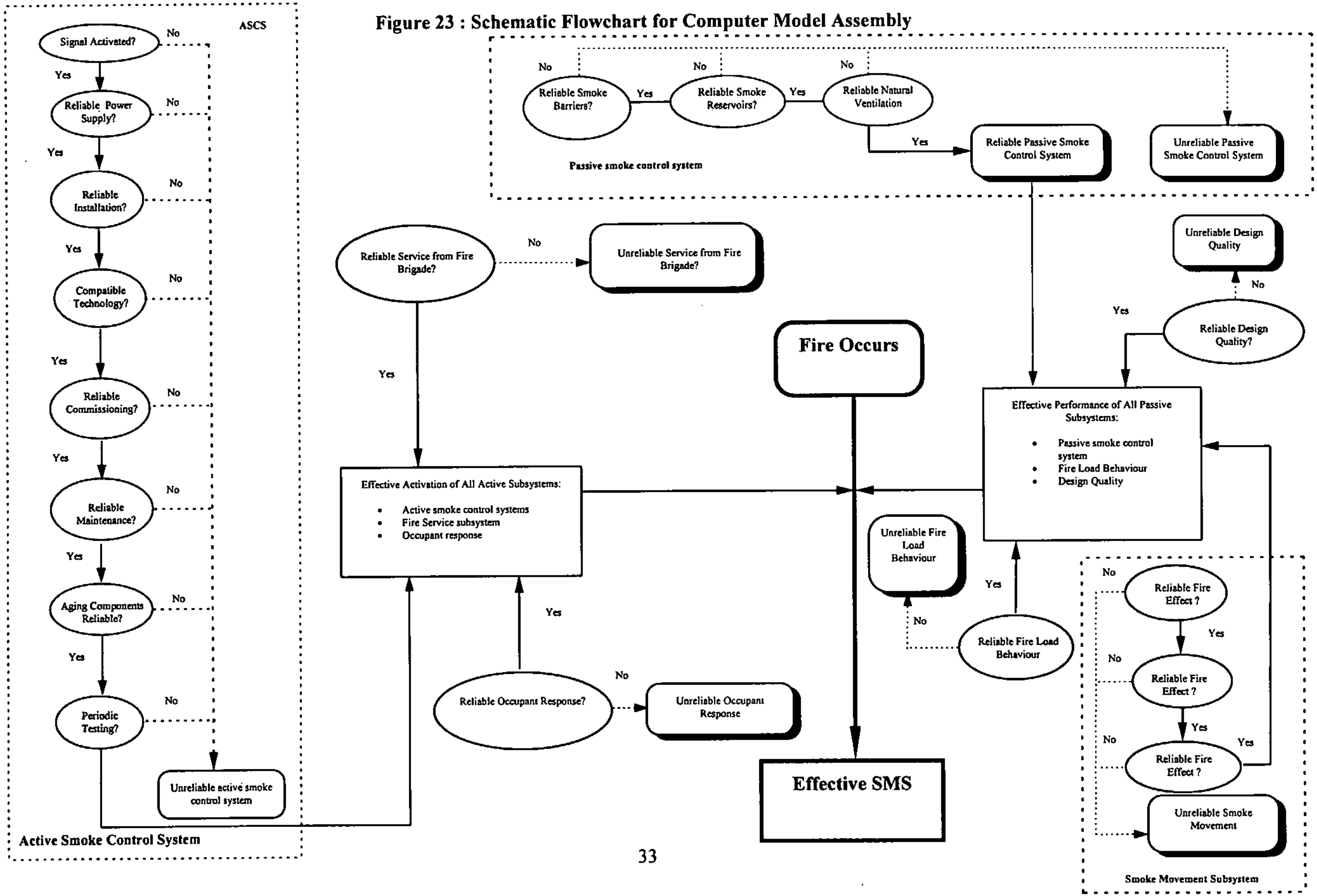


Table 2 : Probability Values

No	Item	Type of Fire											
		Smouldering				Non Flashover				Flashover			
		H	M	L	U	H	M	L	U	H	M	L	U
1	**Signalling System, P_{ss}**												
a	Signals will be activated, P_{ss1}	0.995	0.990	0.985		0.995	0.990	0.985		0.995	0.985	0.975	
b	All active systems will be activated, P_{ss2}	0.995	0.990	0.980		0.995	0.990	0.980		0.995	0.990	0.980	
2	**Power Supply Subsystem, P_{ps}**												
a	Adequate power supply is available, P_{ps1}	1.000	0.990	0.985		0.995	0.985	0.980		0.995	0.985	0.980	
b	Emergency power supply is maintained for required duration, P_{ps2}	1.000	0.990	0.985		0.995	0.985	0.980		0.985	0.975	0.960	
3	**Age of System Components Subsystem, P_{as}**												
a	Active system does not fail due to age of components, P_{as1}	0.995	0.990	0.985		0.995	0.975	0.970		0.995	0.980	0.960	
b	System performs as designed, P_{as2}	0.995	0.990	0.985		0.995	0.975	0.970		0.995	0.980	0.960	
4	**Installation Subsystem, P_{is}**												
a	Installation of ductwork ensures performance as designed, P_{is1}	0.995	0.985	0.980		1.000	0.990	0.980		0.995	0.985	0.980	
b	Electrical installation ensures performance as designed, P_{is2}	0.995	0.985	0.980		1.000	0.990	0.975		0.995	0.985	0.980	
c	Restraint ensures performance as designed, P_{is3}	1.000	0.990	0.985		1.000	0.990	0.975		0.995	0.985	0.980	
d	Installation of backup power supply ensures performance as designed, P_{is4}	0.995	0.985	0.980		1.000	0.990	0.975		0.995	0.985	0.980	
5	**Commissioning Subsystem, P_{cs}**												
a	Individual components perform to specification, P_{cs1}	1.000	0.990	0.985		1.000	0.990	0.980		0.995	0.980	0.970	
b	Flow rate across barriers achieved as designed, P_{cs2}	1.000	0.990	0.985		1.000	0.980	0.970		0.995	0.980	0.970	
c	Flow rate of make up air achieved as designed, P_{cs3}	1.000	0.990	0.985		1.000	0.990	0.980		0.995	0.980	0.970	
d	Flow rate at exhaust equipment achieved as designed, P_{cs4}	1.000	0.990	0.985		1.000	0.990	0.985		0.995	0.980	0.970	
6	**Maintenance Subsystem, P_{ms}**												
a	Repairs during maintenance ensure contained performance, P_{ms1}	1.000	0.990	0.985		1.000	0.990	0.985		0.995	0.990	0.985	
b	System does not fail due to close adherence to program and manual during maintenance checks, P_{ms2}	1.000	0.990	0.985		1.000	0.985	0.980		0.995	0.980	0.970	
7	**Periodic Testing Subsystem, P_{pts}**												
a	System operated for the full design duration during periodic testing, P_{pts1}	1.000	0.990	0.985		1.000	0.985	0.980		0.995	0.985	0.980	
8	**Technology Subsystem, P_{ts}**												
a	System did not fail for required duration due to technologies, P_{ts1}	1.000	0.990	0.980		1.000	0.980	0.975		0.995	0.985	0.980	
9	**Occupant Behaviour Subsystem, P_{os}**												
a	All occupants are alerted to the fire immediately, P_{os1}	0.995	0.980	0.970		0.995	0.980	0.970		0.990	0.980	0.970	
b	All occupants respond to alarm as predicted at design stage, P_{os2}	0.995	0.980	0.970		0.980	0.975	0.970		0.990	0.980	0.970	
10	**Fire Service Subsystem, P_{fs}**												
a	Fire brigade notified immediately on detection of fire/smoke, P_{fs1}	0.995	0.980	0.970		0.990	0.980	0.970		0.990	0.980	0.970	
b	Fire brigade response as predicted at design stage, P_{fs2}	0.995	0.980	0.970		0.990	0.985	0.980		0.990	0.985	0.980	

Table 2 ... continued

No	Item	Smouldering H	Smouldering M	Smouldering L	Smouldering U	Non Flashover H	Non Flashover M	Non Flashover L	Non Flashover U	Flashover H	Flashover M	Flashover L	Flashover U
11	**Smoke Barriers Subsystem, P_{bs}**												
a	Effective location of barriers, P_{bs1}	0.995	0.985	0.980		0.995	0.980	0.975		0.995	0.980	0.975	
b	All gaps between penetrations or construction joints impermeable for design duration, P_{bs2}	0.995	0.985	0.980		0.995	0.985	0.980		0.995	0.975	0.970	
12	**Smoke Reservoir Subsystem, P_{rs}**												
a	Effective location of smoke reservoirs, P_{rs1}	0.995	0.990	0.985		0.995	0.985	0.980		0.995	0.985	0.980	
b	Design volume of reservoir adequate to prevent downward mixing for required duration, P_{rs2}	0.995	0.990	0.985		0.995	0.985	0.980		0.995	0.975	0.970	
13	**Natural Ventilation Subsystem, P_{ns}**												
a	Effective location of natural vents, P_{ns1}	0.995	0.990	0.985		0.995	0.985	0.980		0.995	0.975	0.970	
b	Extraction rates met design requirement for full design duration, P_{ns2}	0.995	0.990	0.985		0.995	0.985	0.980		0.995	0.975	0.970	
14	**Fire Effect Subsystem, P_{fes}**												
a	Maximum fire size and growth rate not greater than that predicted in design, P_{fes1}	0.995	0.990	0.985		0.990	0.985	0.980		0.995	0.975	0.970	
b	Maximum pressure differentials not greater than that predicted in design, P_{fes2}	0.995	0.990	0.985		0.990	0.980	0.975		0.995	0.975	0.970	
15	**Stack Effect Subsystem, P_{ses}**												
a	Pressure differential between the inside and outside of the building at ambient temperature as predicted in design, P_{ses1}	0.995	0.990	0.985		0.990	0.985	0.975		0.980	0.975	0.970	
b	Neutral plane does not drop below design height for required duration of fire, P_{ses2}	0.995	0.990	0.985		0.990	0.985	0.975		0.980	0.975	0.970	
16	**Wind Effect Subsystem, P_{wes}**												
a	Effect of shattering windows as predicted at design phase, P_{wes1}	1.000	0.995	0.990		0.995	0.990	0.985		0.990	0.985	0.980	
b	Wind pressures as predicted at design stage for required duration, P_{wes2}	0.995	0.990	0.985		1.000	0.995	0.990		0.990	0.985	0.980	
17	**Fire Load Subsystem, P_{fls}**												
a	Fire load does not generate more heat and smoke than predicted, P_{fls1}	1.000	0.995	0.990		0.995	0.990	0.980		0.980	0.975	0.970	
b	Flammability effect as predicted at design, P_{fls2}	0.995	0.990	0.985		0.995	0.990	0.980		0.980	0.975	0.970	
c	Effect of vents as predicted at design stage, P_{fls3}	1.000	0.995	0.990		0.995	0.990	0.980		0.980	0.975	0.970	
18	**Design Quality, P_{qs}**												
a	Interface between passive and active systems ensures effective operation for required duration, P_{qs1}	1.000	0.990	0.985		0.995	0.990	0.980		0.980	0.975	0.970	
b	Effective interaction between active and passive subsystems ensures effective performance for required duration, P_{qs2}	1.000	0.990	0.985		0.995	0.985	0.980		0.980	0.975	0.970	

4.3 Active Smoke Control System

4.3.1 Signal Operation

Input	Probability of signals being activated	P_{ss1}
	Probability that signals will activate all active subsystems	P_{ss2}
Calculation	Probability for successful signal operations	$P_{ss} = P_{ss1} \times P_{ss2}$
	Probability for unsuccessful signal operation	$\overline{P}_{ss} = 1 - P_{ss}$
Output	P_{ss} $\overline{P}_{ss}$	

4.3.2 Power Supply

Input	Probability that emergency power supply is available	P_{ps1}
	Probability that emergency power supply is maintained for required duration	P_{ps2}
Calculation	Probability that adequate power supply is available for required duration	$P_{ps} = P_{ps1} \times P_{ps2}$
	Probability that adequate power supply is not available for required duration	$\overline{P}_{ps} = 1 - P_{ps}$
Output	P_{ps} $\overline{P}_{ps}$	

4.3.3 Age of System Components

Input	Probability that ASCS does not fail due to malfunction of aging parts	P_{as1}
	Probability that ASCS with aging parts performs as designed	P_{as2}
Calculation	Probability that ASCS with aging parts operates as designed for required duration	$P_{as} = P_{as1} \times P_{as2}$
	Probability that ASCS with aging parts does not operate as designed for required duration	$\overline{P_{as}} = 1 - P_{as}$
Output	P_{as} $\overline{P_{as}}$	

4.3.4 Installation of ASCS

Input	Probability that installation of ductwork ensures performance of ASCS as designed	P_{is1}
	Probability that electrical installation ensures performance of ASCS as designed	P_{is2}
	Probability that restraints provided ensure performance of ASCS as designed	P_{is3}
	Probability that installation of backup power supply ensures performance as designed	P_{is4}
Calculation	Reliability of installation of ASCS	$P_{is} = P_{is1} \times P_{is2} \times P_{is4} \times P_{is4}$
	Unreliability of installation of ASCS	$\overline{P_{is}} = 1 - P_{is}$
Output	P_{is} $\overline{P_{is}}$	

4.3.5 Commissioning of ASCS

Input	Probability that individual components will perform to specifications during commissioning	P_{cs1}
	Probability that flow rates across barriers will be achieved as designed	P_{cs2}
	Probability that make up air will be achieved as designed	P_{cs3}
	Probability that flow rate at exhaust equipment will be achieved as designed	P_{cs4}
Calculation	Probability that commissioning ensures that ASCS will operate effectively during emergency	$P_{cs} = P_{cs1} \times P_{cs2} \times P_{cs4} \times P_{cs4}$
	Probability that commissioning does not ensure that ASCS will operate effectively during emergency	$\overline{P_{cs}} = 1 - P_{cs}$
Output	P_{cs} $\overline{P_{cs}}$	

4.3.5 Maintenance

Input	Probability that maintenance repairs of ASCS ensures continued performance	P_{ms1}
	Effectiveness of programs and manuals ensures effective operation of ASCS	P_{ms2}
Calculation	Probability that ASCS will operate for required duration due to proper maintenance	$P_{ms} = P_{ms1} \times P_{ms2}$
	Probability that ASCS will not operate for required duration due to poor maintenance	$\overline{P}_{ms} = 1 - P_{ms}$
Output	P_{ms} P_{ms}	

4.3.6 Periodic Testing

Input	Probability that ASCS will operate for required duration during periodic testing	P_{pts1}
Calculation	Probability that ASCS will operate for required duration during emergency due to periodic testing	$P_{pts} = P_{pts1}$
	Probability that ASCS will not operate for required duration	$\overline{P}_{pts} = 1 - P_{pts1}$
Output	P_{pts} $\overline{P}_{pts}$	

4.3.7 New Technology Subsystem

Input	Probability that ASCS will not fail during emergency due to incompatible technology	P_{ts1}
Calculation	Probability that ASCS will not fail during emergency due to incompatible technology	$P_{ts} = P_{ts1}$
	Probability that ASCS will fail during emergency due to incompatible technology	$\overline{P_{ts}} = 1 - P_{ts1}$
Output	P_{ts} $\overline{P_{ts}}$	

4.3.8 Reliability of ASCS

Calculation	Probability that ASCS will operate effectively during emergency	$P_{ascs} = P_{ss} \times P_{ps} \times P_{as} \times P_{is} \times P_{cs} \times P_{ms} \times P_{pts} \times P_{ts}$
	Probability that ASCS will not operate effectively during emergency	$\overline{P_{ascs}} = 1 - P_{ascs}$
Output	P_{ascs} $\overline{P_{ascs}}$	

4.4 Occupant Behaviour

Input	Probability that all occupants will be alerted to the fire immediately	P_{os1}
	Probability that all occupants will respond to the alarm as predicted at design stage	P_{os2}
Calculation	Probability that occupant behaviour prediction is reliable	$P_{os} = P_{os1} \times P_{os2}$
	Probability that occupant behaviour prediction is unreliable	$\overline{P_{os}} = 1 - P_{os}$
Output	P_{os} $\overline{P_{os}}$	

4.5 Fire Service Action

Input	Probability that the fire brigade will be notified immediately on detection of fire/smoke	P_{fs1}
	Probability that fire brigade will respond as predicted at design	P_{fs2}
	Probability that fire brigade will adhere closely to procedures as predicted at design stage	P_{fs3}
Calculation	Probability that service from fire brigade is reliable	$P_{fs} = P_{fs1} \times P_{fs2} \times P_{fs3}$
	Probability that service from fire brigade is unreliable	$\overline{P_{fs}} = 1 - P_{fs}$
Output	P_{fs} $\overline{P_{ff}}$	

4.6 Effectiveness of Active Subsystems

Calculation	Probability that the active subsystems are effective	$\overline{P}_{AS} = P_{ascs} \times P_{fs} \times P_{os}$
	Probability that the active subsystems are ineffective	$P_{AS} = 1 - P_{AS}$
Output	P_{AS} $\overline{P}_{AS}$	

4.7 Passive Smoke Control Systems (PSCS)

4.7.1 Smoke Barriers

Input	Probability that location of smoke barriers is effective	P_{bs1}
	Probability that all gaps and penetrations or construction joints are impermeable for required duration	P_{bs2}
Calculation	Probability that smoke barriers are reliable for required duration	$P_{bs} = P_{bs1} \times P_{bs2}$
	Probability that smoke barriers are unreliable for required duration	$\overline{P}_{bs} = 1 - P_{bs1}$
Output	P_{bs} $\overline{P}_{bs}$	

4.7.2 Smoke Reservoirs

Input	Probability that location of smoke reservoir is effective	P_{rs1}
	Probability that design volume of reservoir is adequate to prevent downward mixing for required duration	P_{rs2}
Calculation	Probability that smoke reservoirs are reliable for required duration	$P_{rs} = P_{rs1} \times P_{rs2}$
	Probability that smoke reservoirs are unreliable for required duration	$\overline{P}_{rs} = 1 - P_{rs}$
Output	P_{rs} $\overline{P}_{rs}$	

4.7.3 Natural Ventilation

Input	Probability that natural vents are effectively located	P_{ns1}
	Probability that design extraction is maintained for required duration	P_{ns2}
Calculation	Probability natural ventilation is reliable for required duration	$P_{ns} = P_{ns1} \times P_{ns2}$
	Probability natural ventilation is unreliable for required duration	$\overline{P}_{ns} = 1 - P_{ns1}$
Output	P_{ns} $\overline{P}_{ns}$	

4.7.4 Passive Smoke Control System

Calculation	Probability that PSCS will be effective for required duration	$P_{pscs} = P_{bs} \times P_{rs} \times P_{ns}$
	Probability that PSCS will not operate effectively during emergency	$\overline{P}_{pscs} = 1 - P_{pscs}$
Output	P_{pscs} $\overline{P}_{pscs}$	

4.8 Smoke Movement Subsystem

4.8.1 Fire Effect

Input	Probability that maximum fire size and growth rate is not greater than that predicted at design	P_{fes1}
	Probability that maximum pressure differential is not greater than that predicted in design	P_{fes2}
Calculation	Probability that fire effect prediction is reliable	$P_{fes} = P_{fes1} \times P_{fes2}$
	Probability that fire effect prediction is unreliable	$\overline{P}_{fes} = 1 - P_{fes}$
Output	P_{fes} $\overline{P}_{fes}$	

4.8.2 Stack Effect

Input	Probability that pressure differential between inside and outside of the building at ambient temperature is as predicted at design	P_{ses1}
	Probability that neutral plane does not drop below design height for required duration	P_{ses2}
Calculation	Probability that stack effect prediction is reliable	$P_{ses} = P_{ses1} \times P_{ses2}$
	Probability that stack effect prediction is unreliable	$\overline{P_{ses}} = 1 - P_{ses}$
Output	P_{ses} $\overline{P_{ses}}$	

4.8.3 Wind Effect

Input	Probability that effect of shattering windows will be as predicted at design stage	P_{wes1}
	Probability that wind pressures will be as predicted at design for required duration	P_{wes2}
Calculation	Probability that wind effect prediction is reliable	$P_{wes} = P_{wes1} \times P_{wes2}$
	Probability that wind effect prediction is unreliable	$\overline{P_{wes}} = 1 - P_{wes}$
Output	P_{wes} $\overline{P_{wes}}$	

4.8.4 Smoke Movement Subsystem

Calculation	Probability that smoke movement will be reliable for required duration	$P_{SM} = P_{fes} \times P_{ses} \times P_{wes}$
	Probability that smoke movement will be unreliable for required duration	$\overline{P_{SM}} = 1 - P_{SM}$
Output	P_{SM} $\overline{P_{SM}}$	

4.9 Fire Load

Input	Probability that fire load distribution does not generate more heat and smoke than that predicted at design Probability that flammability effect will be as predicted at design Probability that effect of vents on fire load will be not greater than that predicted at design	P_{fls1} P_{fls2} P_{fls3}
Calculation	Probability that fire load behaviour as predicted is reliable	$P_{fls} = P_{fls1} \times P_{fls2} \times P_{fls3}$
	Probability that fire load behaviour as predicted is unreliable	$\overline{P_{fls}} = 1 - P_{fls}$
Output	P_{fls} P_{fls}	

4.10 Design Quality

Input	Probability that the interface between passive and active systems is sufficiently simple to ensure effective operation for required duration	P_{qs1}
	Probability that the interaction between active and passive subsystems ensures effective performance for required duration	P_{qs2}
Calculation	Probability that the design of SMS is effective	$P_{qs} = P_{qs1} \times P_{qs2}$
	Probability that the design of SMS is ineffective	$\overline{P_{qs}} = 1 - P_{qs}$
Output	P_{qs} $\overline{P_{qs}}$	

5. SUMMARY

The factors influencing the performance and reliability of SMS in buildings have been identified and examined in this report. A risk assessment technique using success and event tree analysis has been applied to develop a checklist approach for evaluating the effectiveness of SMS. A framework for a simple computer model has also been proposed, based on the findings. The effectiveness measurement of SMS has been based on the:

- Reliability
- Capability, and
- Availability or operational readiness of each component.

The subjective weightings used in the computer model for probability calculations are based on experience. The weightings have been applied based on the impact on the overall system of individual processes or events, and the redundancies provided by them. The weighting selections also enable better comparison of the influence which variations in the effectiveness of individual subsystems have on the overall system.

6. REFERENCES

6.1 Codes and Standards

ASHRAE. 1991. ASHRAE Handbook 1991. Heating Ventilation and Air-Conditioning Applications. SI Edition. American Society of Heating, Refrigeration and Air-Conditioning Engineers Inc. Atlanta. USA.

BSI. 1987. BS 476. Fire Tests on Building Materials and Structures - Parts 20 to 22. Test Methods and Criteria for the Fire Resistance of Elements of Construction. British Standards Institution. London.

BSI. 1989. BS 5588. Fire Precautions in the Design and Construction of Buildings. Part 9: Code of Practice for Ventilation and Air-Conditioning Ductwork. British Standards Institution. London.

Building Industry Authority (BIA). 1992. Approved Document C3/AS1. Spread of Fire. Standards New Zealand.

NFPA, 1991. NFPA 92B. Smoke Management Systems in Malls, Atria, and Large Areas. National Fire Protection Association, Massachusetts, USA.

NFPA. 1993a. NFPA 70. National Electrical Codes. National Fire Protection Association, Massachusetts, USA.

NFPA. 1993b. NFPA 72. National Fire Alarms Codes. National Fire Protection Association, Massachusetts, USA.

Standards Australia (SA). 1990. AS 1530 : Methods for Fire Tests on Building Materials and Structures - Part 4 : Fire Resistance Tests on Elements of Construction. Sydney.

Standards Australia (SA). 1991. AS 1668.1. The Use of Mechanical Ventilation and Air-Conditioning in Buildings. Fire and Smoke Control. Sydney.

Standards New Zealand (SNZ). 1981. NZS 6104. Specification for Emergency Electricity Supply in Buildings. Wellington, New Zealand.

Standards New Zealand (SNZ). 1983. NZS 4219 Specification for Seismic Resistance of Engineering Systems in Buildings. Wellington, New Zealand.

Standards New Zealand (SNZ). 1991. NZS 4238 Code of Practice for Fire Safety in Atrium Buildings. Wellington, New Zealand.

Standards New Zealand (SNZ). 1992. NZS 4203 Code of Practice for General Structural Design. Wellington, New Zealand.

6.2 General

Berl, W.G. and Halpin, B.M. 1980. Human Fatalities from Unwanted Fires. J. Hopkins APL Tech. Dig., 1, p129.

Bowen, J.V. 1988. Reliability. In Section 4 / Chapter 5, SFPE Handbook for Fire Protection Engineering. National Fire Protection Association. Quincy, MA.

Buchanan, A. (editor). 1994. Fire Engineering Design Guide. Centre for Advanced Engineering. University of Canterbury. Christchurch, New Zealand.

Butcher, E.G. and Parnell, A.C. 1979. Smoke Control in Fire Safety Design. E & F N Spon. London.

Fitzgerald, R.W. 1991. Integration of Fire Science into Building Requirements. Fire Safety Journal. Vol 17. pp 159-163.

Klote J.H. 1992. Design of Smoke Management Systems. American Society of Heating, Refrigeration and Air-Conditioning Engineers Inc. Atlanta. USA.

Klote, J.H. and Fothergill, J.W. 1983. Design of Smoke Control Systems for Buildings. National Bureau of Standards, Centre for Fire Research. Washington, DC.

Marchant, E. 1990. Potential Failings of Smoke Control Systems. Fire Prevention No. 230.

Narayanan, P. 1993. Smoke Control in Multi-Storey Buildings. Building Research Association of New Zealand. Study Report No 50. Judgeford, New Zealand.

Narayanan, P. and Whiting, P. 1996. New Zealand Fire Risk Data. BRANZ Study Report No. 64. Building Research Association of New Zealand. Judgeford, New Zealand.

Narayanan, P. 1995. Fire Severities for Structural Fire Engineering Design. BRANZ Study Report No 67. Building Research Association of New Zealand. Judgeford, New Zealand.

Proulx, G. 1995. Evacuation Time and Movement in Apartment Buildings. Fire Safety Journal. Vol. 24, pp 229-246.

Richardson, J.K. 1985. The Reliability of Automatic Sprinkler Systems. Canadian Building Digest CBD 238. National Research Council of Canada. Ottawa.

Pettersson, O. and Jonsson, R. 1988. Reliability Based Design for Fire Exposed Timber Structures - State of Art and Summary Design Guide. TVBB 3040. Department of Fire Safety Engineering. Lund University. Sweden.

Sfintesco, D. et al, 1992. (Editorial Group). Fire Safety in Tall Buildings. Council on Tall Buildings and Urban Habitat Committee 8A. McGraw Hill Inc. New York.

Effectiveness of smoke management system
NARAYANAN, P.
1996 34575

THE RESOURCE CENTRE FOR BUILDING EXCELLENCE

BRANZ MISSION

To be the leading resource for the development of the building and construction industry.

HEAD OFFICE AND RESEARCH CENTRE

Moonshine Road, Judgeford
Postal Address - Private Bag 50908, Porirua
Telephone - (04) 235-7600, FAX - (04) 235-6070

REGIONAL ADVISORY OFFICES

AUCKLAND
Telephone - (09) 526 4880
FAX - (09) 526 4881
419 Church Street. Penrose
PO Box 112-069, Penrose

WELLINGTON
Telephone - (04) 235-7600
FAX - (04) 235- 6070
Moonshine Road, Judgeford

CHRISTCHURCH
Telephone - (03) 366-3435
FAX (03) 366-8552
GRE Building
79-83 Hereford Street
PO Box 496