Open plan flat layouts

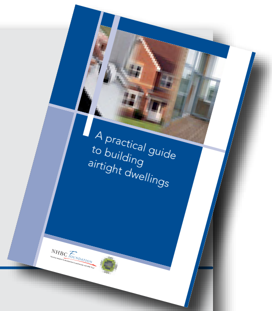
Assessing life safety in the event of fire

NHBC Foundation

Housing research in partnership with BRE Trust

NHBC Foundation publications

A practical guide to building airtight dwellings



A practical guide to building airtight dwellings jointly produced by the NHBC Foundation and the Zero Carbon Hub; it identifies the common air leakage paths and the importance of designing in an air barrier and ensuring that its integrity is maintained throughout the construction phase. ***NF16*** July 2009

Zero carbon compendium – Who's doing what in housing worldwide

The Zero Carbon Compendium, produced in association with the Zero Carbon Hub and PRP is a study of energy and sustainability standards around the world, which allows the UK's plans for zero-carbon housing to be considered from an international perspective. Fifteen countries have been assessed against a framework of questions and presented in a standard format for easy comparison. Case studies for each provide information on the geographic, climatic and statistical indicators for each country as well as a brief review of each country's approach to low-and zero-energy housing. ***NF17*** July 2009

The Code for Sustainable Homes simply explained ***NF15*** June 2009

Zero carbon homes – an introductory guide for housebuilders ***NF14*** February 2009

Community heating and combined heat and power ***NF13*** February 2009

The use of lime-based mortars in new build ***NF12*** December 2008

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Ground source heat pump systems ***NF5*** October 2007

Risks in domestic basement construction ***NF4*** October 2007

Climate change and innovation in house building ***NF3*** August 2007

Conserving energy and water, and minimising waste ***NF2*** March 2007

A guide to modern methods of construction ***NF1*** December 2006

NHBC Foundation publications in preparation

- Impact of airtightness on indoor air quality
- Water efficiency guidelines
- Efficient design of piled foundations
- Sustainable drainage systems for housing

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Steering group members

Association of Consultant Approved Inspectors (ACAI)

BRE

Chief Fire Officers' Association (CFOA)

Communities and Local Government (CLG)

LABC

London Fire Brigade (LFB)

NHBC Building Control Services Ltd

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Scottish Building Standards (SBS)

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FOREWORD

Partly in response to international influences, there has been an increase recently in open plan flat layouts in the UK with bedrooms located as inner rooms. While these designs may appeal to the market, such layouts can pose problems for designers and developers particularly where they may not accord easily with Building Regulations and guidance.

To ensure a more coherent approach and highlight potentially unacceptable risks, this research report has been published for the benefit of designers, housebuilders and building control practitioners. It is hoped that it will contribute to more consistent design and a more straightforward approval process and so benefit the industry and its customers.

This report is the result of a study examining the options for satisfying the requirements of the Building Regulations. It addresses layout, size, travel distances, enhanced detection options and sprinkler use. In addition it addresses the human implications, including the various reactions, wake up and response times from people occupying the building.

Scenario modelling has been undertaken – using a unique evacuation and fire spread computer programme – to compare the risk to life of different layouts and situations. Full results of all the scenarios can be found on the accompanying CD-Rom to assist those who would like more information.

The NHBC Foundation exists to promote good practice within the housebuilding industry. Whether you are involved in designing, building or approving open plan flats I hope this report contributes to your understanding of key factors influencing life safety in the event of fire. I also hope that it contributes to the adoption of safe and consistent solutions.

I hope you find this guide useful – I believe it provides a valuable resource for the industry.

Rt. Hon. Nick Raynsford MP

Chairman, NHBC Foundation

ABOUT THE NHBC FOUNDATION

The NHBC Foundation was established in 2006 by the NHBC in partnership with the BRE Trust. Its purpose is to deliver high-quality research and practical guidance to help the industry meet its considerable challenges.

Since its inception, the NHBC Foundation's work has focused primarily on the sustainability agenda and the challenges of the government's 2016 zero carbon homes target. Research has included a review of microgeneration and renewable energy techniques and the groundbreaking research on zero carbon and what it means to homeowners and housebuilders.

The NHBC Foundation is also involved in a programme of positive engagement with government, development agencies, academics and other key stakeholders, focusing on current and pressing issues relevant to the industry.

Further details on the latest output from the NHBC Foundation can be found at www.nhbcfoundation.org.

NHBC Foundation Advisory Board

The work of the NHBC Foundation is guided by the NHBC Foundation Advisory Board, which comprises:

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EXECUTIVE SUMMARY

This research report describes a study entitled *Assessing life safety of open plan flats layouts* commissioned by the NHBC Foundation and carried out by BRE.

This study involved:

- a literature review, supplemented by questionnaires, to establish the background to the issues of open plan flat layouts and determine what fire safety systems are currently being used in the UK and internationally
- a detailed review of these fire safety systems to identify which of them could be likely to form the best options for meeting the requirements in the UK
- an evaluation of the options using the BRE risk assessment model CRISP to determine the risk levels for selected open plan flats and their equivalent AD B compliant designs.

This report presents the results of this study, the various issues that need to be considered for open plan flats and recommendations.

The report can be used to assist designers, housebuilders, building control practitioners, fire and rescue service personnel and others to design or assess proposed designs for open plan flats to provide a more efficient and consistent design and approvals process which will benefit the housebuilding industry.

This report comprises a summary report supported by appendices and an accompanying CD-Rom. These contain full details of this study and its findings.

CD-Rom

The CD-Rom (found in the pocket at the back of the report) contains PDFs of the graphs relating to the cases discussed in the report and referred to in appendix C. It also includes the results of the sensitivity analysis and the visibility study as PDFs.

GLOSSARY

AD	Approved Document
AFD	Automatic fire detection
C	Conduction loss parameter for heat detectors and sprinklers, in units of $m^{½}.s^{½}$
CFAST	Consolidated Fire And Smoke Transport: Computer zone model, NIST, USA
CRISP	Computation of Risk Indices by Simulation Procedures: Evacuation and fire spread computer model, BRE
DOD	Degree of difficulty: Evacuation parameter within the CRISP model
FED	Fractional effective dose: A measure of exposure of a person to toxic smoke products, when the FED exceeds 1 then a person is incapacitated
LD1	Automatic fire detection system classification. LD1 is more onerous than LD3, see BS 5839-6
LD3	Automatic fire detection system classification, see BS 5839-6
OD	Optical density: Measure of smoke obscuration in units of m^{-1}
OH	Ordinary hazard: A classification of fire hazard for automatic fire sprinkler system design
RTI	Response time index: A measure of how rapidly a heat detector or sprinkler head will react to a rise in temperature, in units of $m^{½}.s^{½}$

1 Introduction

This report describes a study entitled *Assessing life safety of open plan flat layouts* commissioned by the NHBC Foundation and carried out by BRE.

The report comprises a summary report and appendices containing full details of this study and its findings. Appendix A contains the data gathering and literature review; appendix B contains the review and evaluation of systems identified and appendix C contains graphs and tables.

2 Background

Global influences on flat design have led to considerable pressure from developers for open plan layouts, with bedrooms located as inner rooms. This is a significant deviation from guidance provided in Approved Document B (Fire safety) (AD B)[1] that supports the fire safety aspects of the Building Regulations, and may be in conflict with the Regulations themselves. UK-based research to date (mainly by BRE) into the effectiveness of residential sprinklers has shown that they can not be solely relied upon to protect the escape route through a fire-affected room/sleeping accommodation. There has been considerable commercial pressure on building control bodies to approve open plan designs without having any authoritative evidence-based research or guidance on the assessment of open plan arrangements. This has resulted in inconsistency in both design and approvals.

2.1 The study

BRE was commissioned by the NHBC Foundation to carry out a one-year study to assess the life safety of open plan flats in the event of a fire. The objectives of this study were:

- to review the potential methods of meeting Building Regulations' requirements
- to develop concise guidance and a consistent and well-founded knowledge base to assist designers and housebuilders in the design of open plan flat layouts (if possible).

To achieve these objectives, the study was divided into specific tasks which were:

- to form a steering group drawn from interested parties within the industry
- to carry out a literature review to establish the background to the issues of open plan flat layouts and determine what fire safety systems are currently used both in the UK and internationally

- to supplement the literature review by means of a questionnaire sent to building control bodies, fire and rescue services, architects, developers and fire investigators
- to carry out a detailed review of the fire safety systems currently used both in the UK and internationally for open plan flats, and identify which of them could be likely to form the best options for meeting the requirements in the UK
- to evaluate the options identified above using the BRE risk assessment model CRISP
- to present the results of the work to identify the various issues that need to be considered for open plan flats, including regulatory issues, with their various merits and disadvantages
- if possible, to write a guidance document for publication that could be used to assist designers, housebuilders and building control bodies to design or assess proposed open plan flat designs, and to ensure consistency of approach across the industry.

The results from this study are intended to provide input into the development of full UK design standards and to provide the regulators with sound engineering-based results that they can use for regulatory decisions. In the short term, the results from this study are intended to assist those working within the fire arena, offering them the potential to consider alternative approaches to the current guidance contained in AD B.

The ability to provide open plan flats would benefit home owners/occupiers and the flat building industry. Ultimately, it could lead to improved life safety for occupants of open plan flats.

The provision of improved guidance, to be used by building control practitioners and other stakeholders in designing or assessing open plan flat designs, should result in a more efficient and consistent design and approvals process which will benefit the housebuilding industry.

2.2 Steering group

The study was guided by a steering group which was established at the start of the study and met three times during the course of the work programme. The steering group members included representatives of the NHBC Foundation, NHBC Building Control Services Ltd, Communities and Local Government (CLG), LABC, Association of Consultant Approved Inspectors (ACAI), Chief Fire Officers' Association (CFOA), London Fire Brigade (LFB) and Scottish Building Standards (SBS). They provided general advice and review on all aspects of the methodology of the study.

3 Literature review and questionnaire

Relevant data and information were collected and a literature review of work carried out to establish the background to the issues of open plan flat layouts and determine what fire safety systems are currently used in the UK and internationally.

Information and data were collected via a combination of:

- steering group members
- targeted questionnaire
- published literature
- web search
- anecdotal information and data known to BRE.

There is limited published information and data in the public domain that is relevant to the issue of open plan flat designs. The bulk of the collected information is anecdotal, obtained from BRE and steering group members' experiences and from questionnaire responses.

3.1 Existing guidance

The functional requirement of Part B1 of Schedule 1 to the Building Regulations 2000 for England and Wales[2] states: "The building shall be designed and constructed so that there are appropriate provisions for the early warning of fire, and appropriate means of escape in case of fire from the building to a place of safety outside the building capable of being safely and effectively used at all material times."

There are two distinct components to planning means of escape from buildings containing flats: escape from within each flat, and escape from each flat to the final exit from the building. This study is focused on escape from within individual flats.

AD B[1] guidance includes restrictions on inner rooms and provides three approaches for internal layouts to:

- provide a protected entrance hall serving all habitable rooms with a maximum travel distance to the entrance door from the door from any habitable room of 9 m; or
- limit the travel distance to the entrance door from any point in any of the habitable rooms to 9 m and locate cooking facilities remote from the entrance door; or
- provide an alternative exit or exits from the flat.

Open plan layouts, by definition, do not satisfy the first approach. The second approach is effectively limited to studio flats/bedsits, by virtue of the constraint on size (travel distance), and the third option is only likely to be economically viable for flats on the ground or first floor. Therefore, open plan flats are effectively discouraged. (One response to the questionnaire described this as 'guidance by omission'.)

AD B also provides for the installation of a smoke alarm/smoke alarms within the entrance hall to an LD3 standard, in accordance with British Standard BS 5839-6.[3]

AD B provides for sprinkler protection, in accordance with BS 9251[4] for apartment buildings over 30 m in height. This is a provision above and beyond the other measures, and there are no variations or design freedoms in the internal flat layout or duration of fire resistance offered for sprinklered flats over 30 m in height.

The Scottish government has recently issued a consultation paper which includes proposals for the use of smoke alarms to an LD1 standard together with sprinklers or another suitable automatic fire suppression system in dwellings.[5]

The National Fire Protection Association (NFPA), USA, Life Safety Code 2006 edition[6] generally assumes that flats (particularly new-build) will have provision for smoke and/or heat detection, and will have sprinkler systems installed. There are different restrictions on travel distances, depending on whether the building is new or existing, and the fire protection strategy employed. Where there are sprinklers, the restrictions on travel distances are eased, and the detection requirements are less onerous. It is interesting to note that the allowed travel distances within the flat, even without sprinklers provided, are much longer than those given in AD B.

3.2 Possible justification for open plan flats

A number of arguments have been put forward by designers and fire engineers to justify why departures from AD B should be allowed, enabling open plan flats to be built.

The arguments include the following points:

- Travel distance could be limited to that allowed for a bedsit (9 m), although with inner room(s) (which AD B does not allow).
- Enhanced detection and alarm systems could be provided, beyond what is specified in AD B.
- Sprinklers or other suppression systems could be provided.
- 'Upside-down' (two level) flats, with bedrooms on the lower level and lounge, kitchen, etc on the upper level, would reduce the consequences of fires while people are asleep.
- AD B no longer includes the requirement for fire-resisting doors to have self-closers. Therefore, it is assumed that these doors will be open. The question is how this is different from an open plan layout.
- Fire modelling may be employed to demonstrate acceptable safety.

Each of these arguments attracts a counter-argument to justify why open plan flats should not be allowed. Much of the difficulty in resolving the merits of one argument versus another lies in the fact that statements are almost always qualitative in nature. Fire and smoke movement modelling, where it is carried out correctly, can provide a quantitative, deterministic analysis of alternative approaches. These analyses can be used in comparative studies to demonstrate equivalency. However, the assumptions made in practice by the users of these models can be highly subjective and do not typically address human factors, with the result that the arguments may not be conclusive one way or the other.

3.3 Questionnaire analysis

A questionnaire was developed and circulated to:

- steering group members
- selected architects/developers
- building control bodies (ACAI and LABC members)
- fire and rescue services
- selected fire safety engineers.

There were 30 responses to the questionnaires; 15 respondents have been involved in the design or approval of proposed open plan flat designs. There is no evidence for open plan designs being concentrated in a particular geographical region (but the data set is too small to identify any but the most obvious trends).

Ten questionnaire respondents provided descriptions of schemes with open plan flat layouts that they had encountered. In general, these designs had:

- limited travel distances, similar to code-compliant designs (the longest distance quoted was 23 m; most were shorter)
- enhanced detection (7 of the 10 cases described; usually L1 standard, in accordance with BS 5839-6 if details were given), and sprinkler provision (the same 7 out of 10 cases).

Despite these common features in designs, there was not much consistency in whether or not the designs were approved. For example, two respondents each described different schemes where travel distance was limited, and enhanced detection and sprinklers were provided. In one case the scheme was approved; in the other it was not. The only difference seems to be whether the bedroom doors had self-closers. On the other hand, some schemes have been approved although enhanced detection and sprinklers were not specified.

The majority of questionnaire respondents were not happy with the existing guidance on fire safety as it applies to open plan flats. Only three thought it was sufficient. The general tone of the responses was that the guidance does not address what developers want to build (open plan layouts with inner rooms); acceptable designs presumably do exist, but there is no guidance as to what these designs might be.

A number of comments were received, arguing that each scheme should be considered on its own merits, with fire safety engineering used for justification. However, at least one other person felt it was too time-consuming and costly to repeat this process every time, and that more prescriptive guidance was preferable.

Among the responses in favour of prescriptive guidance, it was suggested that such guidance should acknowledge that enhanced detection plus sprinklers would meet the requirements of the Building Regulations for open plan flat designs.

One of the drawbacks of considering each scheme individually is that the level of proof required needs to be agreed by discussion between the designer and the building control practitioner. Without adequate guidance, this is likely to perpetuate the current inconsistent approach to the design and approval process.

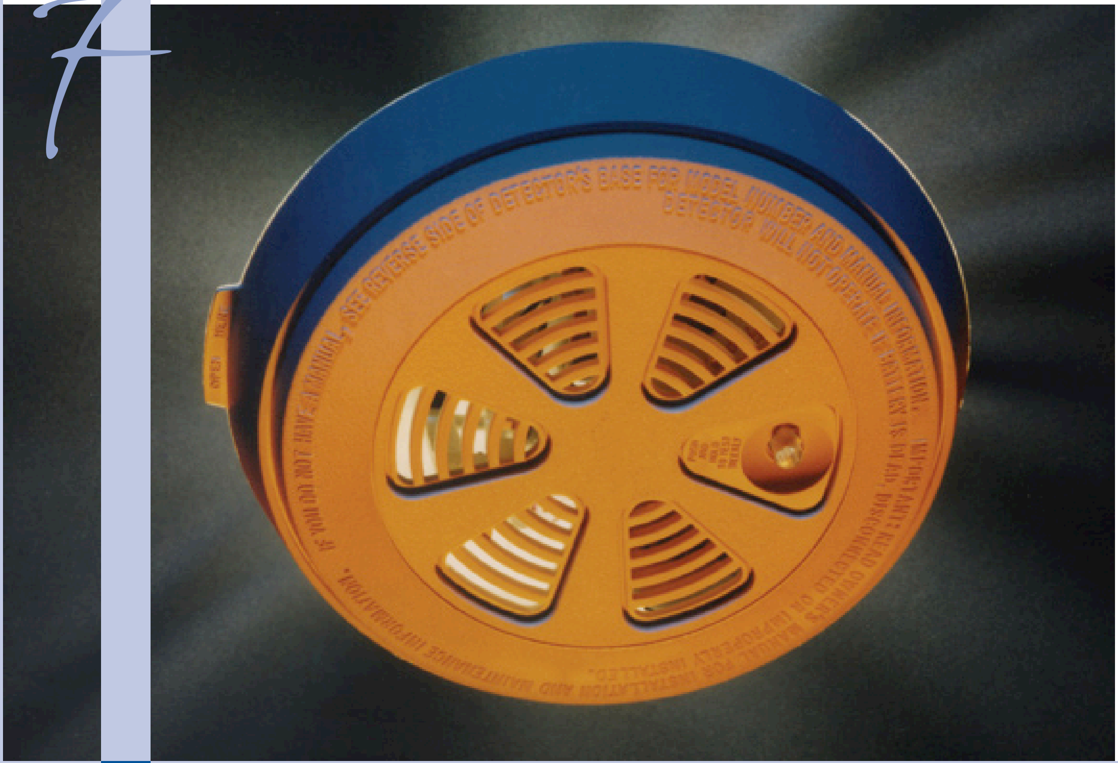
3.4 The effectiveness of residential sprinklers

BRE has carried out several studies on residential sprinklers on behalf of Communities and Local Government.[7,8] One extensive study[7] comprised a cost–benefit analysis, benchmark tests and an experimental programme. In the experiments, the effectiveness of the sprinklers was primarily assessed by measuring their ability to control toxicity, temperature and visibility in the fire room and connected spaces.

The conclusions of the experimental programme were:

- For the majority of scenarios studied experimentally, the addition of residential sprinkler protection proved effective in potentially reducing casualties in the room of fire origin and connected spaces.
- Sprinkler protection was not found to be a panacea; slow-growing and shielded fires can be a problem.
- Smoke alarms, fitted in the room of fire origin, responded typically in half the time required by sprinklers and well before the conditions had become life-threatening.
- Closing the door to the room of fire origin, in both sprinklered and unsprinklered cases, can be effective in keeping tenable conditions in connecting spaces.

It is worth noting that, although the risk to life was lowered, the cost–benefit analysis did not recommend sprinklers as an additional safety measure in most cases. (High rise blocks of flats above 30 m high were an exception, where they were worthwhile, although it should be noted that these conventional flats did not include open plan flats.)



4 Assessment of open plan flats with different fire protection systems

It was noted earlier that the arguments used to justify open plan layouts were predominantly qualitative in nature. Even in cases where fire modelling was used, various limitations, such as the small number of scenarios considered, and failure to include aspects such as human behaviour, meant that the results were inconclusive.

In this study, there has been an endeavour to address these limitations by using the BRE risk assessment model, CRISP, to compare different flat design options.

4.1 The modelling approach

CRISP is the BRE evacuation and fire spread computer model. It is a Monte Carlo model of entire fire scenarios.[9–11] Monte Carlo methods are experiments based on random numbers, usually produced by a computer. In this application, the Monte Carlo simulation approach models individual fire scenarios and, like an opinion poll, uses a limited but representative sample of these scenarios to infer an estimate of the risk to life arising from all possible fires. Deterministic sub-models describe the different processes and events taking place during the fire. Initial values for each run, and the outcomes of events during the scenario, can be sampled from suitable statistical distributions. Monte Carlo simulations are ideally suited to practical applications, since there is the opportunity to include a high level of detail where necessary, and complex conditional probabilities.

The sub-models representing physical 'objects' (Fig. 1) include rooms, doors, windows, sprinklers, detectors and alarms, items of furniture, hot smoke layers and people. The randomised aspects include starting conditions such as various windows and doors open or closed, the number, type and location of people within the building, the location of the fire and type of burning item.

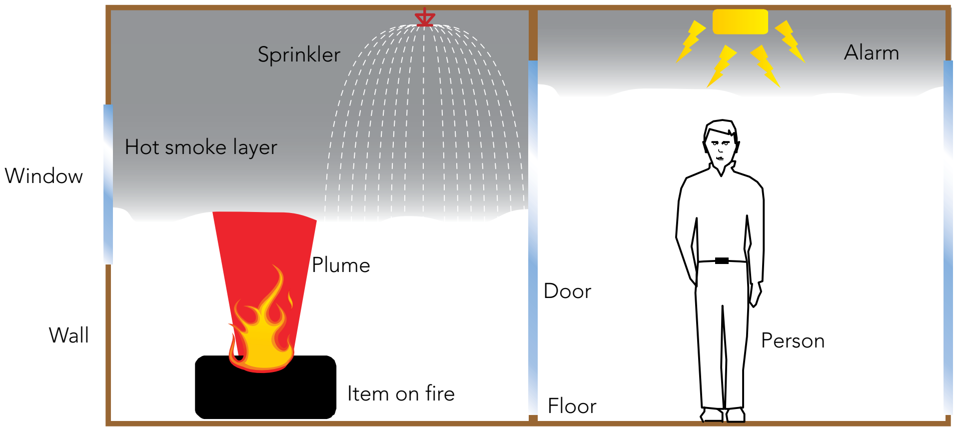


Figure 1 A pictorial representation of the primary physical 'objects' in the CRISP simulation.

As the people move around the building, they may be exposed to toxic smoke and acquire a fractional effective dose (FED).[12] When the FED reaches 100%, the person is defined as 'dead'. The risk can be expressed simply in terms of the fraction of people originally present who become 'dead', averaged over a sufficiently large Monte Carlo sample. Alternatively, the risk can be expressed as the average number of fatalities per fire.

The main advantages of using CRISP, rather than other models, are:

- It is a system model of 'everything', not just smoke movement from a pre-determined fire growth rate.
- It considers a very wide range of different fire scenarios.
- It can model a wide range of different fire safety strategies, including differences in human behaviour.
- It relies on first principles (ie physical laws) wherever possible (albeit with simplifying approximations where appropriate).
- It has been validated for use in domestic occupancies using experimental data, and real fire incident data for human behaviour.
- By calculating the risk to life, it provides an ideal metric for the comparison of different designs.

4.2 Case studies

Nine cases have been modelled, in three groups of three. The three groups represent a one-bedroom flat/bedsit, a medium-sized two-bedroom flat, and a large three-bedroom flat. Within each group there are three options, based on a similar floor plan, representing an AD B compliant case, an alternative case, and the alternative case plus sprinkler protection. These case studies were agreed following discussions with the steering group.

The nine cases are shown in Figures 2 to 10.

Group 1

Group 1 is a one-bedroom flat or bedsit, with a footprint of 8 m × 4 m. The AD B compliant case represents a bedsit (case 1a), and the alternative has the bedroom as an 'inner room' accessed from the living room/kitchen (case 1b). There is also an alternative with additional sprinkler protection (case 1c). These cases are shown in Figures 2 to 4.

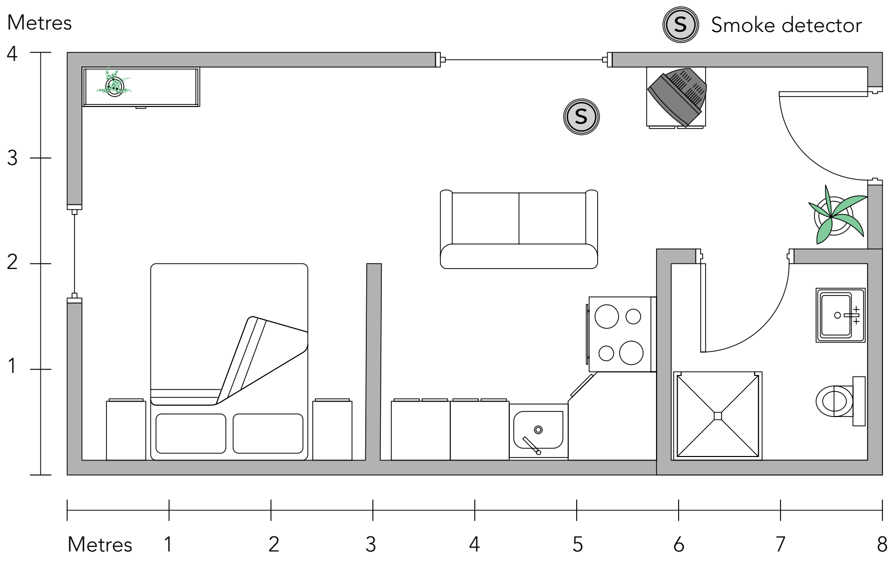


Figure 2 Case 1a.

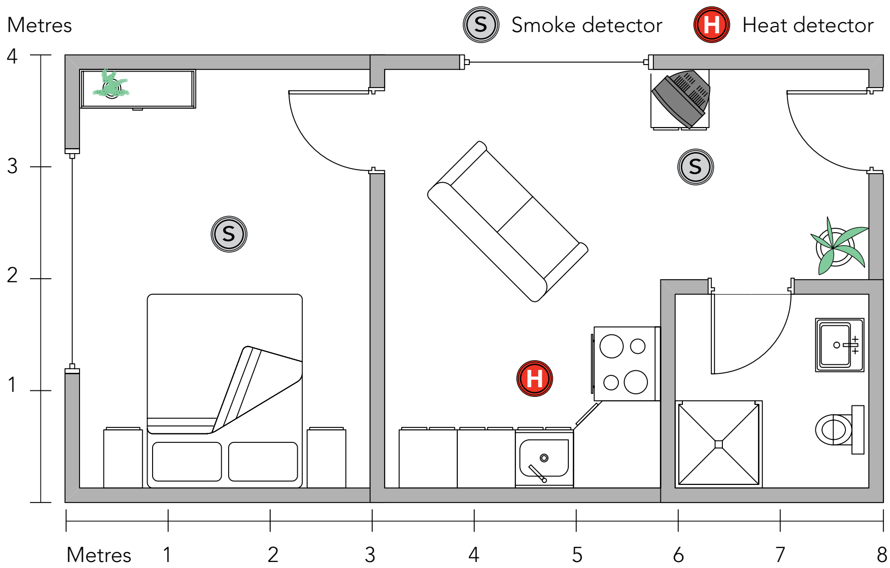


Figure 3 Case 1b.

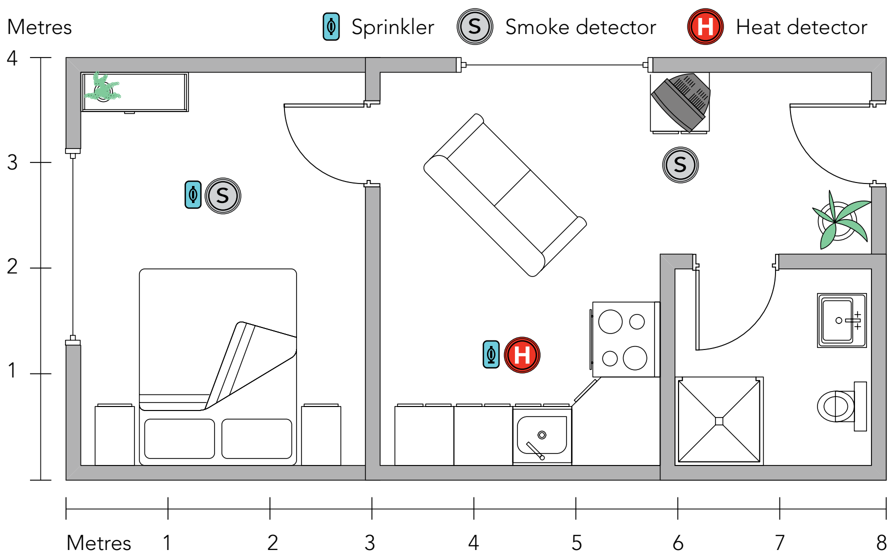


Figure 4 Case 1c.

Group 2

Group 2 is a two-bedroom flat, with a footprint of 10 m × 8 m. The AD B compliant case includes a hallway (case 2a), and the alternative has an open plan lounge with the bedrooms as 'inner rooms' accessed directly from the lounge (case 2b). There is also an alternative with additional sprinkler protection (case 2c). These cases are shown in Figures 5 to 7.

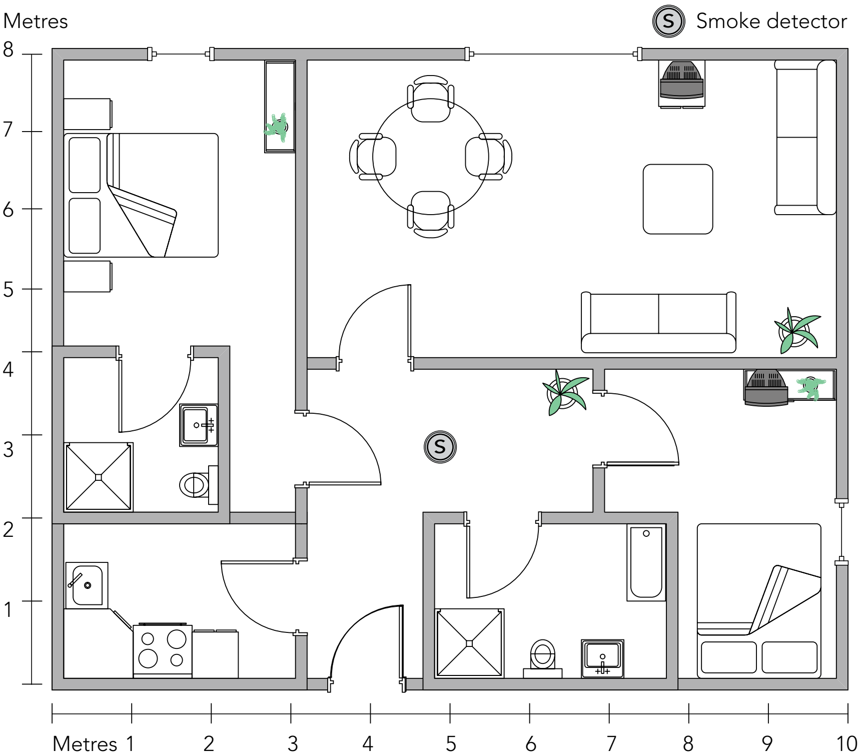


Figure 5 Case 2a.

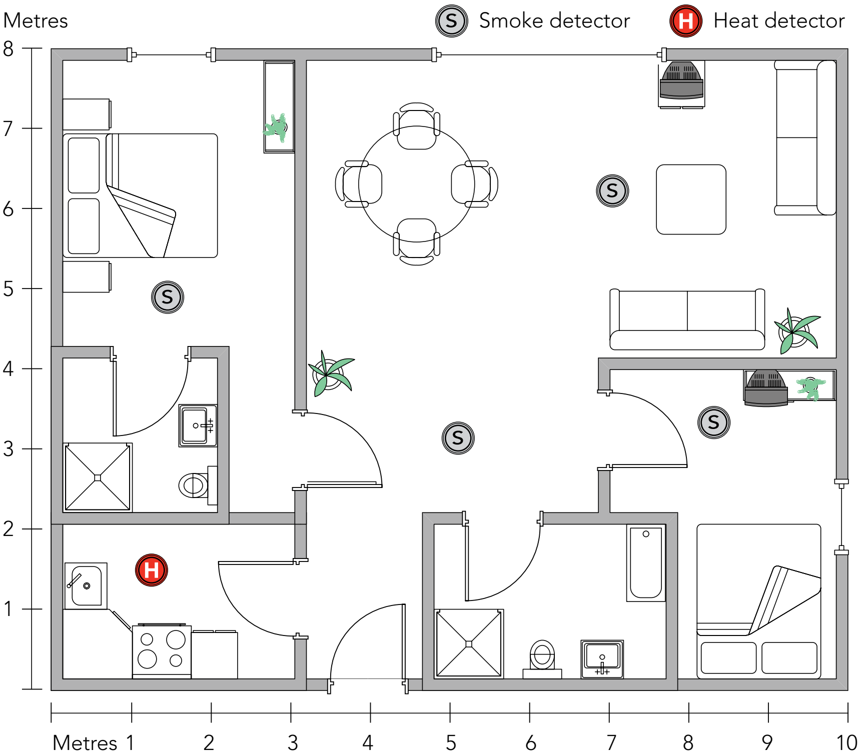


Figure 6 Case 2b.

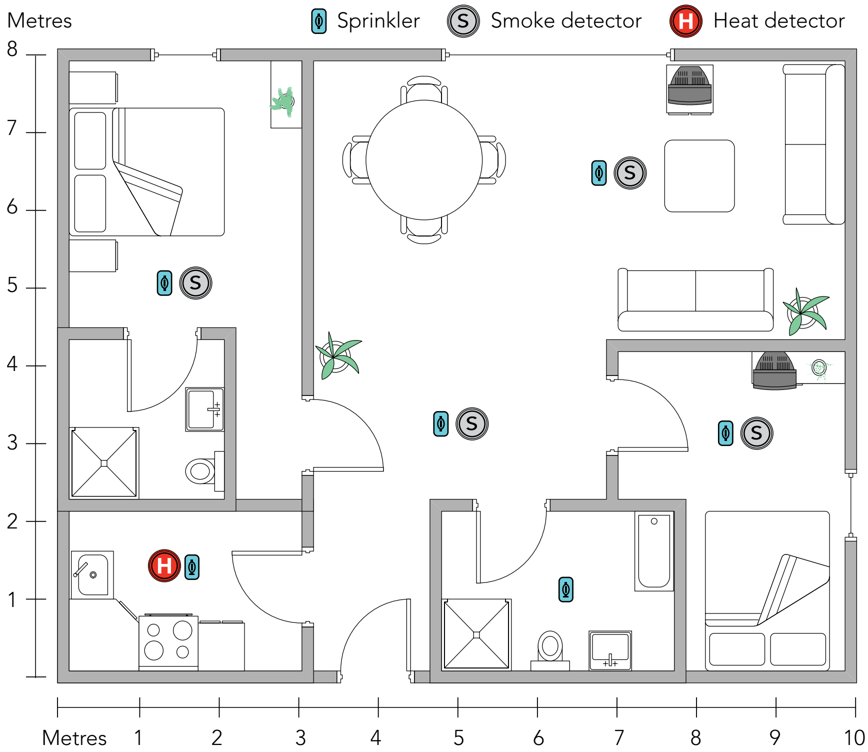


Figure 7 Case 2c.

Group 3

Group 3 is a three-bedroom flat, with a footprint of 16 m × 12 m. The AD B compliant case includes a hallway (case 3a), and the alternative has an open plan lounge with the bedrooms as 'inner rooms' accessed directly from the lounge (case 3b). There is also an alternative with additional sprinkler protection (case 3c). These cases are shown in Figures 8 to 10. They are intended to be compared against the group 2 cases to investigate the importance of travel distance.

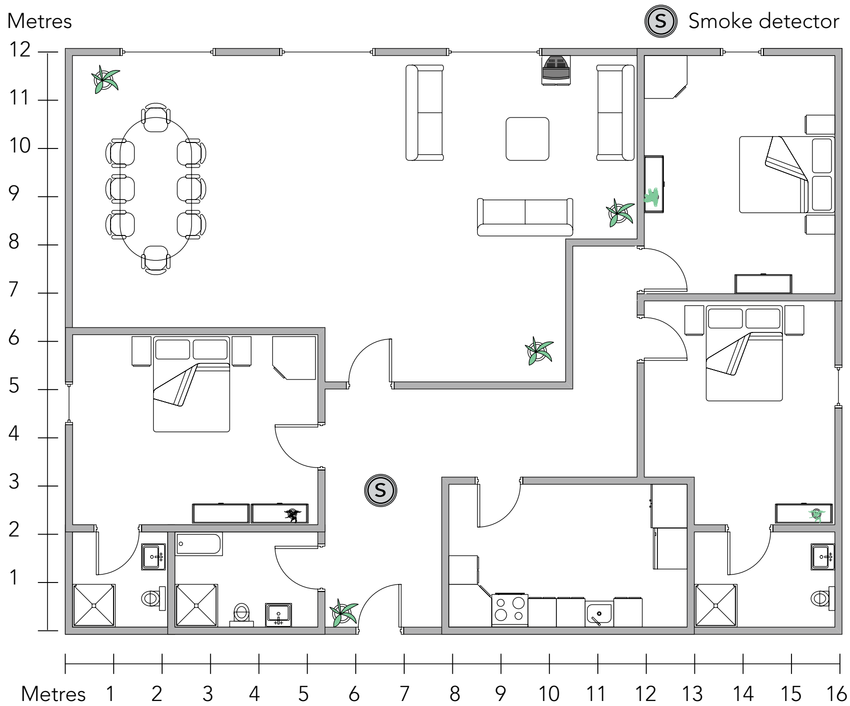


Figure 8 Case 3a.

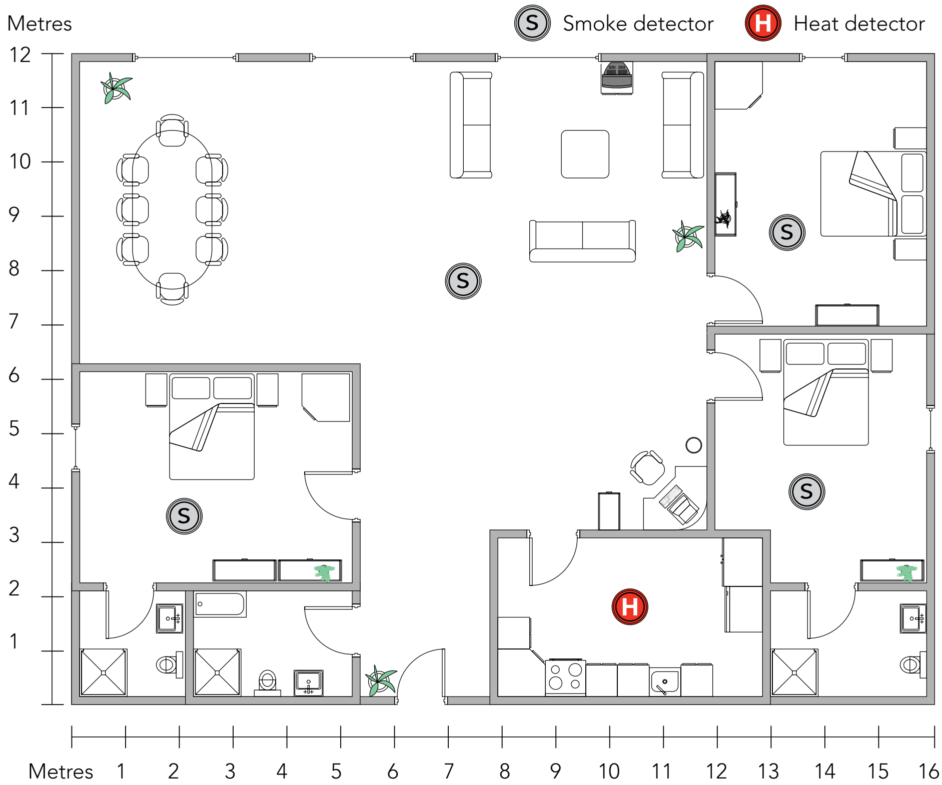


Figure 9 Case 3b.

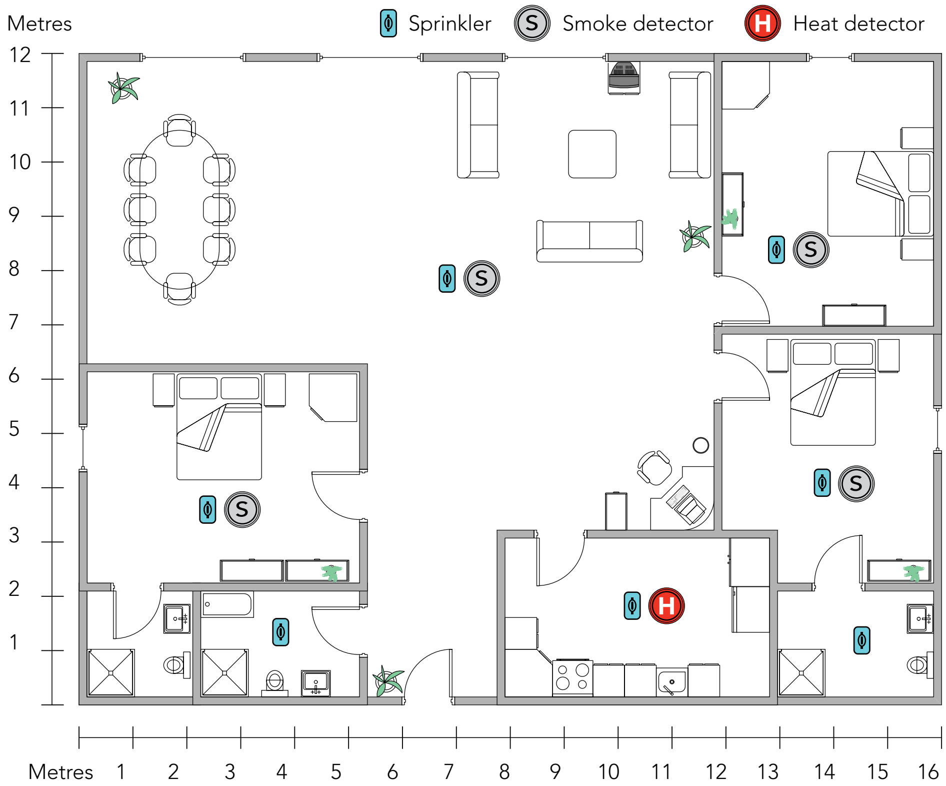


Figure 10 Case 3c.

Appendix B describes the modelling work and contains full details of:

- geometry and dimensions of each flat layout
- thermal properties of the walls
- range of fire scenarios considered (fire location within the flat, time of day or night, type of burning item, possible fire spread beyond item first ignited, etc)
- ventilation (probability of doors or windows being open or shut, probability and extent of window breakage when exposed to heat, etc)
- active fire protection systems (characteristics of smoke detectors, heat detectors, and sprinklers)
- characteristics of human population (numbers of adults, elderly people and children, sleeping patterns, arousal thresholds, other characteristics)
- behavioural 'rules' for different people types.

The nine cases are summarised in Table 1.

Table 1

Summary of the CRISP modelling cases

Case	Bedrooms	Configuration	Footprint*	Alarms	Sprinklers
1a	One (studio/bedsit)	AD B compliant	8 m × 4 m	LD3‡	No
1b	One	Open plan/inner room†	8 m × 4 m	LD1§	No
1c	One	Open plan/inner room†	8 m × 4 m	LD1§	Yes
2a	Two	AD B compliant	10 m × 8 m	LD3‡	No
2b	Two	Open plan/inner room	10 m × 8 m	LD1§	No
2c	Two	Open plan/inner room	10 m × 8 m	LD1§	Yes
3a	Three	AD B compliant	16 m × 12 m	LD3‡	No
3b	Three	Open plan/inner room	16 m × 12 m	LD1§	No
3c	Three	Open plan/inner room	16 m × 12 m	LD1§	Yes

* Ceiling height is 2.4 m in all cases.
† 9 m travel distance measured to back of inner room case.
‡ LD3 system, smoke alarm in the circulation space.
§ LD1 system, smoke alarm in each room.

4.3 Results

4.3.1 Main results

For each of the nine cases, Figure 11 shows the average number of people per fire whose FED is >1%, >10%, >30% and 100%. These represent progressively more severe levels of exposure; when FED reaches 100% the person is defined as being 'dead'. With a FED of >10% a person would almost certainly be recorded as an 'injury' in the fire statistics for a real fire. A FED of ~1% might be sufficient for a person to be sent to hospital for a precautionary check. Note that people with a FED>10% form a subset of people with a FED>1%, people with a FED>30% form a subset of people with a FED>10%, etc.

These results suggest that enhanced detection can achieve similar levels of risk to AD B compliant designs. Enhanced detection plus sprinklers results in significantly lower risk. Refer to appendix B (section 6.7) for a detailed discussion of these results.

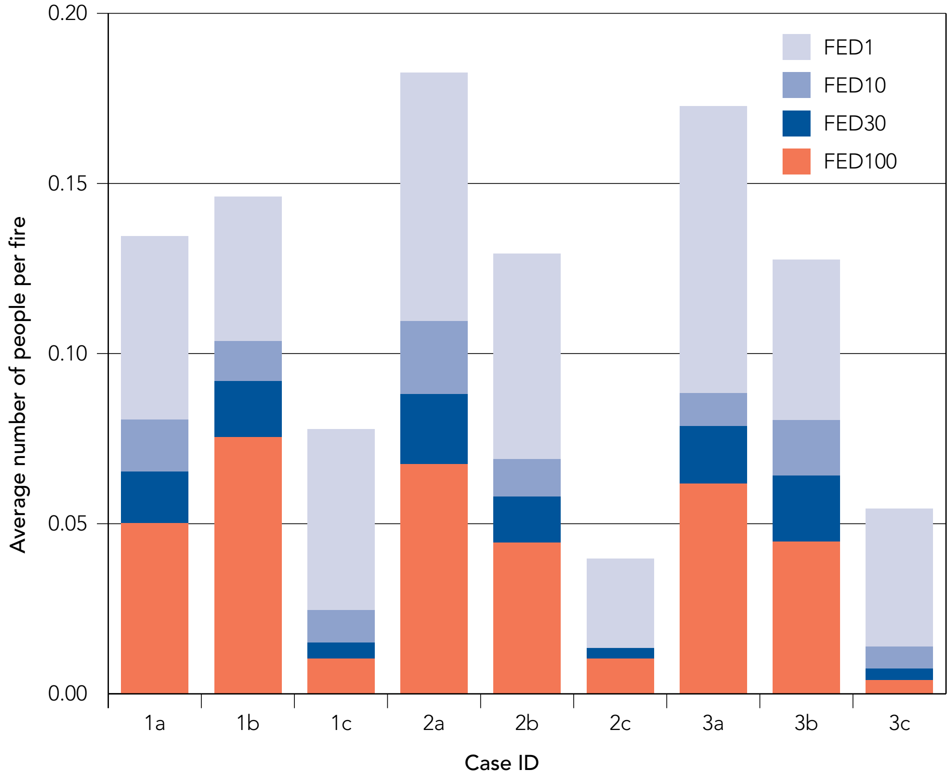


Figure 11 Main results. Risk of death or different levels of injury for each case.

4.3.2 Sensitivity analysis

During the study, it was considered worthwhile to investigate the sensitivity of the model predictions to the assumptions that had been made concerning the amount of time people required to react to an alarm, or to awaken from sleep.

For the sensitivity analysis, the 'weighted average FED' was used as the risk metric. The weighted average FED is the average, per fire, of the sum of the dose received by all the people at risk from that fire. As shown in a previous paper,[10] this is a good measure for the overall risk since it is strongly correlated with the number of deaths but has a lower fractional error.

The results are shown in Figure 12.

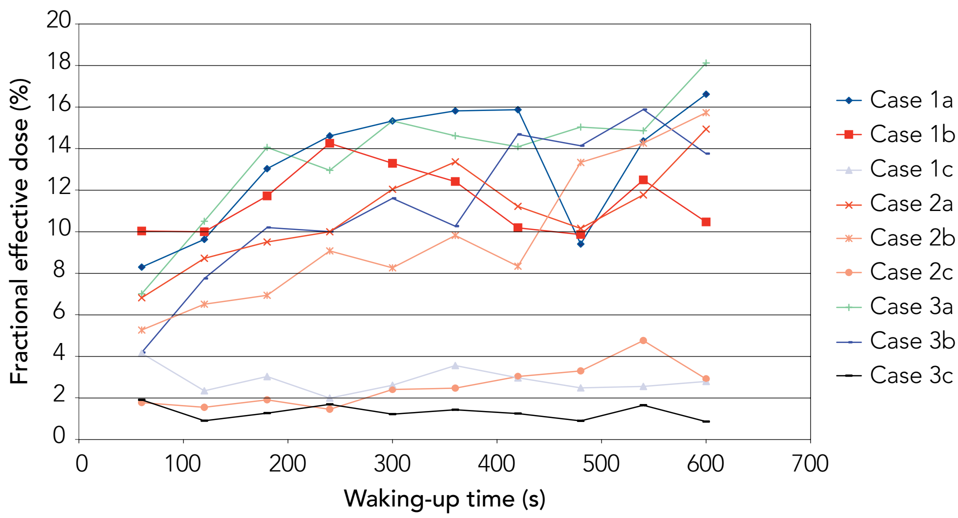


Figure 12 Sensitivity analysis results. Fractional effective dose per fire as a function of the time required to wake up.

The time taken by a person who is awake to react to an alarm did not seem to make much difference to the risk, based on average toxic dose. The results were more sensitive to the time taken by sleepers to wake up. If Figure 12 is examined closely, it is possible to see that for values of the waking-up time less than 300–400 s, the relative risk for cases 2b and 3b (inner rooms with enhanced detection and alarm coverage) is consistently lower than that for cases 2a and 3a (conventional flat designs with hallways). Refer to appendix B (section 6.8) for a detailed discussion of these results. More work is needed to understand precisely why the toxic doses should be lower in cases 2b and 3b, compared with the corresponding cases 2a and 3a.

For very large values of the waking-up time (greater than ~400 s), the results for cases 1a, 1b, 2a, 2b, 3a and 3b become more or less random, with no discernible trends and large variability. More work is needed to understand and explain the reasons for this randomness. This behaviour does reduce confidence in relying only on detection and alarms to achieve a level of safety equivalent to that of an AD B compliant design.

In cases 1a (bedsit) and 1b (inner room with enhanced detection and alarm coverage), the trend is less clear, with similar risks in both cases. It may be that the extra detection and alarm in case 1b is providing some compensation for the smaller room sizes which would lead to faster smoke-filling times, compared with case 1a. In the two- and three-bedroom flats, reduced risks are obtained for the cases with enhanced detection and alarm coverage and a larger living room, compared with their conventional design counterparts.

In order to better understand the complex interplay between the various dynamic factors, it is recommended that the risks for open plan designs with no additional fire protection features are also evaluated for comparison with the above results. Currently, it is not possible to say with a sufficiently high degree of confidence that enhanced detection alone will be at least as good as an AD B compliant design.

However, it is very clear that, regardless of the assumptions made about the time required to wake up following an alarm, sprinklers are beneficial (Fig. 12, cases 1c, 2c, 3c).

4.3.3 Visibility analysis

One of the main questions that arises with the qualitative arguments and residential sprinklers work is whether occupants of inner rooms would be trapped by smoke in the open plan area. So further work was carried out to look at visibility, in particular.

The simulations have been investigated in more detail where one or more people were 'trapped' (eg unable to reach an exit due to the severity of the smoke), even if this only applied for a brief duration. The proportion of simulations where someone was 'trapped' is shown in Figure 13.

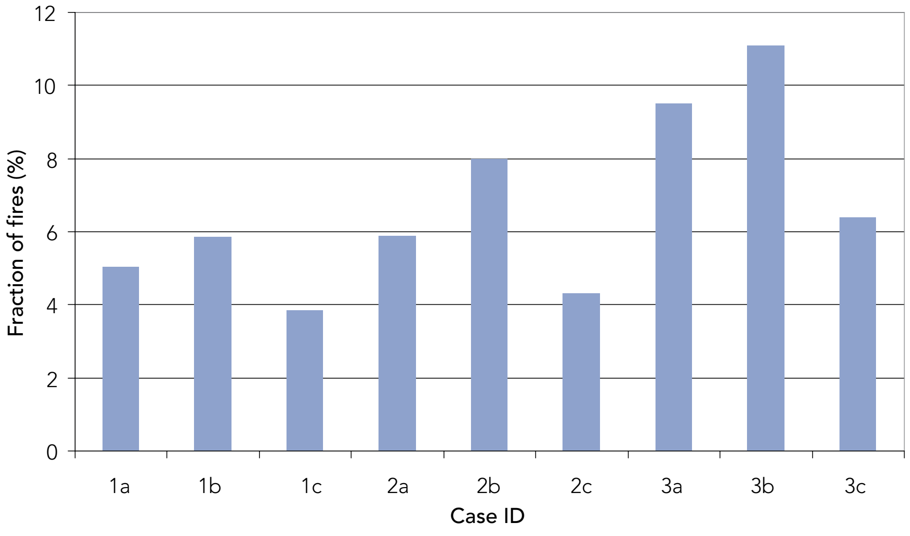


Figure 13 The fraction of fires where smoke prevents escape.

The cases where there are sprinklers present, cases 1c, 2c and 3c, all have a lower proportion of fires where people are trapped, compared with the corresponding cases where there are no sprinklers. This is evidence that sprinklers do make it easier for people to escape, rather than only reducing the risk by enabling people to survive for extended periods when trapped within the building.

Note that the fraction of fires where smoke prevents escape is higher for enhanced detector and alarm coverage (cases 2b and 3b), compared with the corresponding conventional flat designs (cases 2a and 3a), although other results have previously shown that cases 2b and 3b have lower risk, based on the FED calculations. This is a further reason why enhanced detector and alarm coverage, without also including sprinklers, is not recommended as a means of ensuring that open plat flats have risks that are the same as or lower than equivalent AD B compliant designs.

A very crude model of sprinkler downdrag was incorporated into the CRISP simulation. For this model, it was assumed that whenever a sprinkler operated, the room would become impassable as a result of downdrag. People would leave if already within the room, but would not enter if they were outside it. Re-running the sprinklered cases with this model produced outcomes identical to those for the version of the model without downdrag. Therefore it is clear that by the time a sprinkler operated, conditions in the room of fire origin were so bad that people would not enter that room anyway, whether or not downdrag occurred.

However, sprinklers can reduce the chance of people being trapped by smoke in rooms other than that of the fire origin. Consider an example where there is a fire in a bedroom, and people in other bedrooms (all bedrooms adjoining the living room). People need to pass through the living room in order to escape. When the sprinkler in the room of fire origin operates and the fire is extinguished or controlled, there will be less smoke entering the living room; therefore people in other rooms will be more likely to be able to pass through.

These results enhance the robustness of the conclusion that sprinklers significantly reduce the risk in open plan flats. More results are presented in appendix C.

4.3.4 Maintenance of active fire protection systems

It is essential, and the modelling has assumed, that these active fire protection systems (detection and sprinklers) will be maintained in accordance with their recognised standards to achieve appropriate levels of performance and reliability.

4.4 Conclusions and guidance

4.4.1 Conclusions of the study

This study was carried out to assess the life safety of open plan flats. A literature review, supplemented by questionnaires, established the background to the issues of open plan flat layouts and determined what fire safety systems are currently being used in the UK and internationally. An evaluation of some potentially promising options using the BRE risk assessment model CRISP determined the risk levels for selected open plan flats and their equivalent AD B compliant designs.

The main conclusions of the study are:

- These results indicate that open plan flats with a sprinkler system (in accordance with BS 9251[4] or BS EN 12845,[13] as appropriate) and an enhanced detection system (LD1 system in accordance with BS 5839-6[3]) can provide a level of safety that is at least as good as that of a similar AD B compliant design.
- Flat size/travel distance has been shown not to be a significant factor (up to the largest size considered here: 12 m × 16 m). However, this result should not be extrapolated to larger designs without further analysis.
- It is not possible to state with sufficient confidence that enhanced detection alone could satisfy the requirements of the Building Regulations.

- A fire-engineered solution should consider all aspects of the whole fire system, including fire growth, smoke movement, detection, suppression, human behaviour and interactions between them.
- Without consideration of human behaviour, depending on the scenario, fire models might not give an adequate measure of the risk.

These conclusions apply to the specific layouts examined and the simulations carried out using the CRISP model and the parameters as defined in appendix B. Therefore, it is important that any practitioner using the guidance within this document for the design of open plan flat layouts satisfies themselves that the parameters defined in appendix B are appropriate to their design.

The CRISP model has been validated for use in domestic occupancies, using data from experimental fires in real buildings and other computer models. This validation is limited to physical aspects such as fire growth, smoke movement, and detector and sprinkler operation. Real fire incident data have been used to derive 'rules' for human behaviour. However, this study did not include an experimental validation that could be directly compared to any of the fire scenarios modelled in the case studies.

The modelling has assumed that these active fire protection systems (detection and sprinklers) will be maintained in accordance with their recognised standards to achieve appropriate levels of performance and reliability.

This study did not investigate the effect of:

- flats larger that 12 m × 16 m
- multi-level apartments
- smoke control systems
- water mist and other suppression systems
- an open plan kitchen close to the front door
- self-closing doors on the inner rooms.

More work is needed if conclusions about comparisons of risks of death and injuries can be drawn for cases that are significantly different from the specific cases studied.

4.4.2 Guidance for designers

As guidance for designers of open plan flat designs and for the scenarios described in appendix B of this report, active fire protection comprising: a sprinkler system in accordance with BS 9251[4] or BS EN 12845[13] as appropriate; and an enhanced detection and alarm system (LD1) in accordance with BS 5839-6[3] can provide a level of safety that is at least as good as that of a similar AD B compliant design.

These recommendations should not be applied to open plan designs that differ significantly from the cases that have been examined in this study. For example: flats larger that 12 m × 16 m; multi-level flats; flats with smoke control systems, water mist and other suppression systems; flats with open plan kitchens close to the front door; and flats in blocks of more than 30 m in height. Other differences include the characteristics of the occupants: for example 'retirement' flats would have a much greater proportion of families comprising solely elderly occupants than the 'typical' populations that have been considered in this study.

In such cases, further work is required to determine the level of safety relative to a comparable AD B design. A fire-engineered solution should consider all aspects of the whole fire system, including fire growth, smoke movement, detection, suppression, human behaviour and interactions between them.

The choice and siting of detectors should be carefully considered, to avoid the incidence of false alarms in open plan arrangements.

5 Further work

Recommendations for further work are to carry out the following:

- An evaluation of the risks in open plan designs without the benefits of sprinklers or enhanced detection and alarm coverage, in order to improve understanding of the complex interactions between different factors, and provide further evidence whether or not enhanced detection and alarm coverage provides a satisfactory risk level without the inclusion of sprinklers.
- Determination of the upper limit on travel distance for flats larger than 12 m × 16 m in plan area with similar layouts.
- Assessment of the fire safety of large luxury flats (with an appropriate occupant population).
- Assessment of the fire safety of other designs, eg multi-level flats.
- Extension of case studies to real case examples that are significantly different from those already studied.
- An evaluation of the effect of different occupant characteristics on the risk. This study used occupant characteristics that represented the overall UK population. Other occupant profiles should be studied specifically, eg single-parent families, elderly people, disabled people, extended families.
- An experimental confirmation of selected scenarios for enhanced detection and sprinklers to validate the findings of this work, reduce modelling uncertainty and enhance the robustness of the conclusions of this study.
- A study of the effect of the location of the kitchen on the risk of being trapped. This would include consideration of the effect of an open plan kitchen close to the front door.
- Experimental studies to assess the fire safety of designs involving water mist systems.

- Assessment of the fire safety of designs involving other fire protection systems, eg smoke control, self-closing doors.
- A sensitivity study of the effect of increased alarm coverage in all rooms rather than just the hallway.

6 Appendices

APPENDIX A

Details of data gathering and literature review

6.1 Data gathering and literature review

Relevant data and information were collected and a literature review of work carried out to establish the background to the issues of open plan flat layouts and determine what fire safety systems are currently used in the UK and internationally.

Information and data were collected via a combination of:

- steering group members
- targeted questionnaire
- published literature
- web search
- anecdotal information and data known to BRE.

A questionnaire was developed and circulated to:

- steering group members
- selected architects/developers
- building control bodies (Association of Consultant Approved Inspectors and LABC members)
- fire and rescue services
- selected fire safety engineers.

A copy of this questionnaire is shown on page 41.

A second, modified questionnaire was prepared for fire investigators and circulated via the International Association of Arson Investigators UK Chapter. A copy of the questionnaire for fire investigators is shown on page 42.

All of the information collected has been reviewed to provide a fully informed view of the fire safety issues of fires in open plan flats. Salient information is included in section 6.2.5.

6.2 Findings

There is limited published information and data in the public domain that is relevant to the issue of open plan flat designs.

The bulk of the collected information is anecdotal, obtained from BRE and steering group members' experiences and from questionnaire responses.

The information and data have been reviewed and the findings are as follows.

6.2.1 Approved Document B provisions

The functional requirement of Part B1 of Schedule 1 to the Building Regulations 2000 for England and Wales[2] states: "The building shall be designed and constructed so that there are appropriate provisions for the early warning of fire, and appropriate means of escape in case of fire from the building to a place of safety outside the building capable of being safely and effectively used at all material times."

There are two distinct components to planning means of escape from buildings containing flats: escape from within each flat and escape from each flat to the final exit from the building. This study is focused on escape from within individual flats.

AD B[1] provides guidance on the internal layout of flats to reduce the risk of people becoming trapped by a fire. The guidance includes restrictions on inner rooms and provides three approaches for internal layouts to:

- provide a protected entrance hall serving all habitable rooms with a maximum travel distance to the entrance door from the door from any habitable room of 9 m
- limit the travel distance to the entrance door from any point in any of the habitable rooms to 9 m and locate cooking facilities remote from the entrance door
- provide an alternative exit or exits from the flat.

Open plan layouts, where the escape routes from bedrooms are via the living spaces, can meet these provisions, but only where an alternative escape route from the bedrooms is available.

For floors less than 4.5 m above ground level (ground and first storey), this can be achieved with escape windows. For floors above 4.5 m, additional common circulation spaces/stairways are necessary, which renders this type of layout economically unviable.

AD B also provides for the installation of a smoke alarm/smoke alarms within the entrance hall to an LD3 standard, in accordance with BS 5839-6.[3]

Sprinkler protection is included in the AD B guidance for apartment buildings over 30 m in height, in accordance with BS 9251.[4] This is a provision above and beyond the other measures and there are no variations or design freedoms in the internal flat layout or duration of fire resistance offered for sprinklered flats over 30 m in height.

6.2.2 Review of other standards

British Standard BS 9999

British Standard BS 9999[14] offers advice on inner rooms. Clause 17.3.4 states: "An inner room arrangement is acceptable if … the inner room is not a bedroom." BS 9999 does not cover flats.

The Building (Scotland) Regulations 2004

The Technical Standards[15] supporting the Scottish Building Regulations[16] follow principles similar to those provided in England and Wales in AD B. However, the Scottish government has recently issued a consultation paper which includes proposals for giving the option of either a passive or an active approach in dwellings.[5]

The proposed active approach has no requirement to construct internal walls to protect the route of escape. Instead, protection is provided by the use of smoke alarms to an LD1 standard together with sprinklers or another suitable automatic fire suppression system.

NFPA Life Safety Code 2006 edition, USA

The NFPA Life Safety Code[6] contains the following provisions.

In general, flats (particularly new-build) will have provision for smoke and/or heat detection, and will have sprinkler systems installed. Where there are sprinklers, the restrictions on travel distances are eased, and the detection requirements are less onerous.

In new buildings, sprinklers are not required if all dwellings have:

- direct access to an exit at ground level, or
- direct access to an exterior stair, that serves at most two units, both on the same floor, or
- direct access to a private interior stair, separated from the rest of the building by a one-hour fire-resisting construction.

In existing buildings, sprinklers are not required if all dwellings have:

- direct access to an exit at ground level, or
- a fire engineering solution has been adopted.

In a partially sprinklered existing building, sprinklers are only required in the common access corridors, and just inside the door to each dwelling.

In a new building with sprinklers, single-point smoke alarms are required on every floor, outside bedrooms. Alarms are not required in the common parts if the building does not exceed four storeys in height and 16 dwellings in total.

In a new building without sprinklers, single-point smoke alarms are required on every floor, outside bedrooms, and also in every sleeping room. Alarms are not required in the common parts if each flat is separated from the others by a one-hour fire-resisting construction, and has its own direct exit or stair.

Existing buildings are described by one of four options:

- option 1 – no fire detection or suppression system
- option 2 – complete automatic fire detection and warning system
- option 3 – partial automatic sprinkler coverage
- option 4 – full automatic sprinkler coverage.

In option 2, smoke detectors and alarms are required in all common parts, and heat detectors and alarms in each room of the flat. In options 3 and 4, smoke detection and alarm is required outside each bedroom.

Alarms must include visible warning signals, to cater for the hard of hearing.

There are different restrictions on travel distances, depending on whether the building is new or existing, and on the fire protection strategy employed. These are given in Table 2.

It is interesting to note that the allowed travel distances within the flat are much longer than those given in AD B.

Table 2

Travel distances specified in NFPA 101: Life Safety Code[6]

	Travel distance (m)					
	New buildings		Existing buildings			
	Sprinklers	No sprinklers	Option 1	Option 2	Option 3	Option 4
Within flat, to front door	38	23	23	38	23	38
Dead ends in common parts	15	10.7	15	15	15	15
Common path in common parts (ie not inside flat)	15	10.7	10.7	10.7	10.7	15
Flat door to exit	61	30	30	46	46	61
Exterior exit path	61	61	61	61	61	61
Furthest part of common part from exit	76	61	Not mentioned			

6.2.3 Justifications for the fire safety designs of open plan flats

The most common qualitative arguments presented for the fire safety designs of open plan flats from BRE experience, and confirmed by steering group members at the first steering group meeting, are as follows.

Restricted travel distances (up to 9 m)

It can be argued that restricting the travel distance from inner rooms to entrance doors can provide an equivalent level of safety to that provided in AD B compliant studio flats. Sometimes the 9 m is measured from the furthest point in the inner room and on other projects it is measured from the door to the room (Figs 14 to 16).

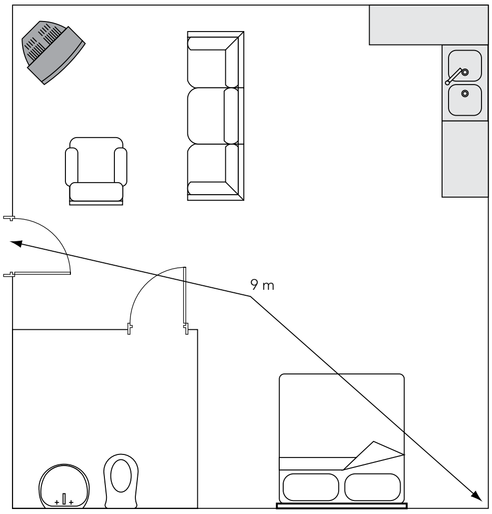


Figure 14 AD B compliant studio flat.

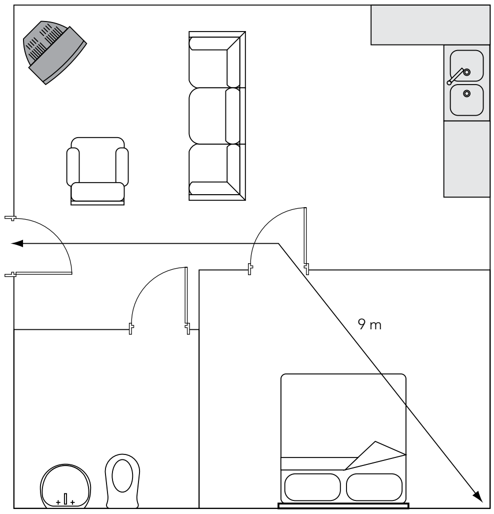


Figure 15 Alternative approach – 9 m measured to back of inner room.

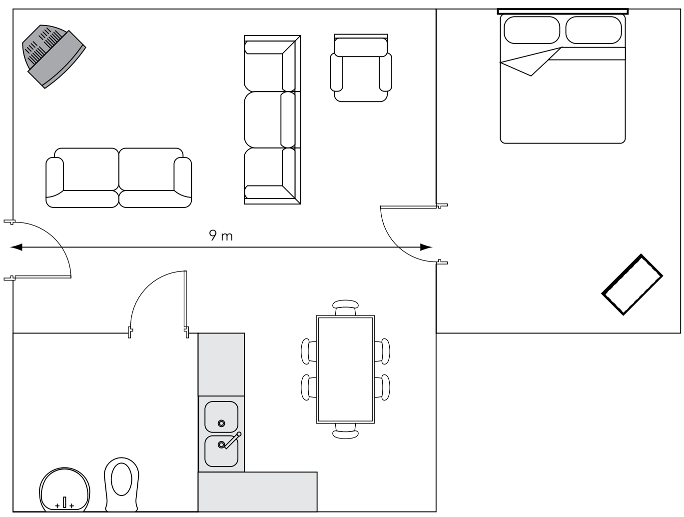


Figure 16 Alternative approach – 9 m measured to door of inner room.

Provision of enhanced automatic fire detection and alarm system

It is sometimes argued that smoke alarms provided within an access room would detect a fire much earlier than alarms in an adjacent protected hallway. Providing extra alarms in the inner rooms could also provide better audibility and enhance the probability that occupants would be roused in an emergency (Figs 17 and 18).

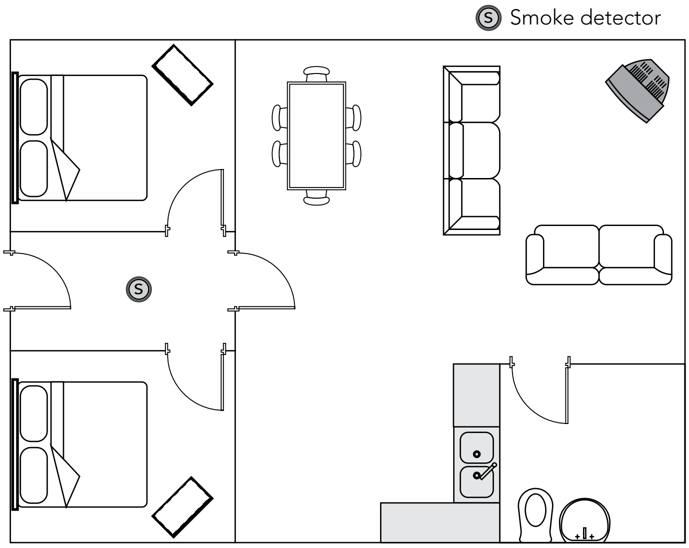


Figure 17 AD B compliant flat – smoke alarm in entrance hall.

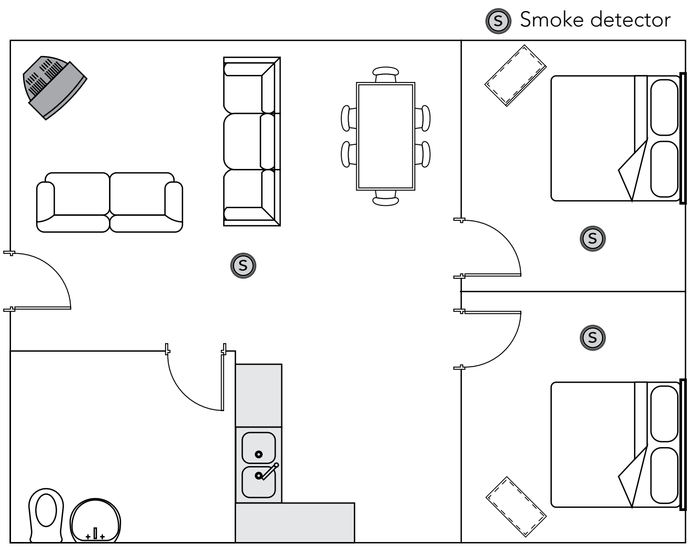


Figure 18 Alternative approach – smoke alarms in bedrooms and access room.

Provision of sprinklers or other fire suppression system

Sprinkler protection may be considered as an alternative to the physical (passive) enclosure of escape routes. The presumption is that sprinklers will be able to ensure that tenable conditions are maintained in the escape routes. Sprinklers are often proposed in conjunction with fire detection on the grounds that, in a slower developing fire, the early warning system alone should provide the occupants with sufficient time to escape, and where the fire develops more quickly the sprinkler system should control the fire and maintain tenability (Fig. 19).

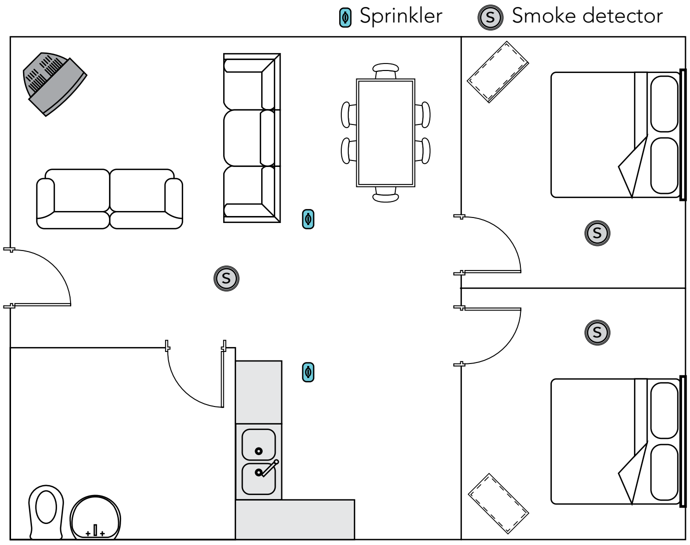


Figure 19 Alternative approach – smoke alarms in bedrooms and access room and sprinklers in access room.

'Upside down' multi-storey flats

For multi-storey flats, some designs are arranged so that the sleeping accommodation is located on the entrance storey, with the living space located above it (Figs 20 and 21). The living space is open plan with no separation from the circulation routes. In terms of the guidance in AD B, this still renders the bedrooms as inner rooms but it can be argued that the occupants of the bedrooms do not have to escape through the living space and that the natural buoyancy of smoke offers a degree of protection.

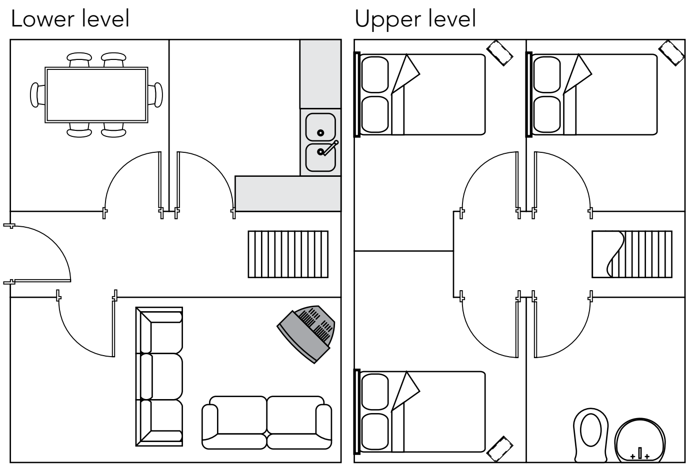


Figure 20 Conventional AD B compliant two-storey flat.

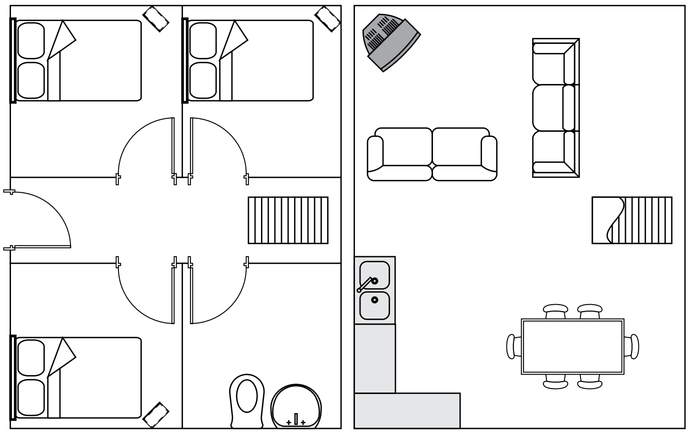


Figure 21 Alternative approach – two-storey 'upside down' flat.

The extent and quality of evidence used by designers and fire engineers to support their strategies varies greatly. Some of the more common forms of evidence used to support these strategies are as follows.

Statistical evidence

Engineers often quote the experience of installing sprinklers in areas such as Scottsdale, Arizona.[17] These clearly demonstrate that sprinkler protection reduces the occurrence of fire casualties, but they do not provide direct correlation to proposed design freedoms or equivalency to passive approaches.

Fire modelling evidence (of fire and smoke behaviour)

Fire modelling, where it is carried out correctly, can provide deterministic analyses of alternative approaches. These can be used in comparative studies to demonstrate equivalency. However, the assumptions used in these models can be highly subjective and do not typically address human factors.

Removal of door closers

In the current edition of AD B, self-closing devices are no longer necessary on fire-resisting doors located within a dwelling.

Some engineers have argued that it can be assumed that these doors will be left in the open condition for the purposes of comparative studies and effectively the dwelling will be open plan.

6.2.4 Steering group members' comments

Steering group members' comments from the first steering group meeting are summarised as follows:

- The nature of the people (eg mobility-impaired, social lifestyle) needs to be taken into account in this study.
- Each design needs to be fully fire-engineered, eg BS 7974[18] approach.
- Not all of the open plan flat designs involve the use of sprinklers.
- The UK is unlike other countries in having building standards that apply inside dwellings.
- There is a need to cover the principles of AD B (Requirement B1) in the report.

- AD B compliant does not mean trapped in your room for an extended period, albeit safely.
- What does 'safe' mean in the context of AD B of the Building Regulations?
- Consideration needs to be given to how the findings of this study will be delivered in the final report.
- The final report cannot say what will or will not comply with the Building Regulations but can provide information on the relative risks of different solutions.
- It was suggested that the open plan flat scenarios be divided into two categories – 'small open plan flats with <9 m travel distance' and 'large luxury open plan apartments with much longer travel distances' – which will have different types of occupants/socio-economic factors.
- Some of the open plan flat designs have water mist systems rather than sprinklers. There is currently no standard for residential water mist systems in the UK/Europe.
- Some of the designs have smoke control systems, eg via plenum ceilings.
- Another scenario is when the kitchen can be located near to the front door of the flat.
- Should fire and rescue service activities be considered/included?
- If sprinklers are included for open plan flats, which standard should be applied, BS 9251[4] or BS EN 12845[13]? This needs further clarification outside this study.
- Potential AD B compliant solutions, such as 'kick-out panels' and linked balconies, could provide an alternative means of escape.
- Confidence in systems, eg maintenance, needs to be taken into account.
- From real fires experience, management issues need to be taken into account, eg an active system can be turned off/made inactive or accidentally damaged.

6.2.5 Questionnaire findings

Questionnaire responses

There were 30 responses to the questionnaires. Table 3 shows a breakdown of the response by category and whether they have answered 'yes' or 'no' to the question of whether respondents have been involved in the design or approval of proposed designs of open plan flats in the UK. Fifteen respondents have been involved in the design or approval of proposed open plan flat designs.

Table 3

Questionnaire responses

Respondent	Yes	No	Total
Approved inspector	2	0	2
Architect	2	0	2
Developer	0	0	0
Fire authority – Fire prevention officer	3	2	5
Fire engineer	2	0	2
Local authority building control officer	5	13	18
Other – Fire safety consultant	1	0	1
Total	15	15	30

The collated responses to the questionnaire are presented in the following sections.

Geographical area in the UK

The questionnaire respondents reported that buildings with open plan flat layouts are found in London, Salford, Manchester, Birmingham, Bristol, Reading, Croydon, Buckinghamshire, Milton Keynes, Sheffield and the South East of England, and randomly spread across the UK.

Roughly, how many buildings with open plan flat layouts in the UK have you or your company dealt with and were these open plan flats approved?

The questionnaire respondents had experience of the following buildings with open plan flat layouts:

a) two buildings with a total of 600 flats, approved

b) one scheme with four apartment blocks with a mixture of open plan and hallway access designs, containing approximately 100 units, approved

c) several proposed schemes that show increased travel distances from AD B provisions

d) a couple formally, but quite a few enquiries

e) many approved over the years

f) three buildings containing 75 flats

g) 100 plus approved

h) approximately ten buildings containing single-storey and duplex flats, seven of which are approved and the remainder ongoing

i) four schemes at the concept stage containing single-storey flats and two of these were approved

j) six to twelve schemes, approximately two of these approved

k) one or two four-storey buildings with single-storey and duplex flats, not approved

l) 25, not approved

m) three blocks of high-rise single-storey apartments and one block of low-rise, two approved.

In addition there were a number of projects where opinion was sought on open plan flat layout designs which fall outside the current AD B guidance (and also advice given on design codes). However, no further details were provided in the questionnaire returns.

Details of proposed designs

Details of the designs are summarised as follows.

a) ***Two buildings containing 600 single-storey and duplex flats.*** The overall flat dimensions, open plan room dimensions, types of rooms and numbers of each type have been supplied. Salient details are:

- The travel distance to the final exit for the open plan room is 18 m maximum.
- The travel distance to the final exit from the furthest inner room is 18 m.
- There is an enhanced fire detection system, L1, with direct activation of room of origin.
- There is an OH3 sprinkler system, covering the whole building.
- There are doors with closers to the bedrooms.

b) *One scheme containing four apartment blocks.* The apartment block contains approximately 100 single-storey units, with a mixture of open plan and hallway access designs. The overall flat dimensions, open plan room dimensions, types of rooms and numbers of each type have been supplied. Salient details are:

- The travel distance to the final exit for the open plan room is 6 m.
- The travel distance to the final exit from the furthest inner room is 12 m.
- There is an enhanced fire detection system. Smoke detectors are provided everywhere except for the bathrooms and storage closets.
- There is a BS 9251[4] compliant sprinkler system, with quick-response sprinkler heads and connected to the fire alarm system.
- There is an entrance door with door closer from the common corridor into the open plan area; doors to bedrooms off the open plan area; bathroom door off the open plan area; door to ensuite, tank/storage room door off the open plan area.

c) *Several proposed schemes that show increased travel distances from AD B provisions.* No further details have been provided.

d) *A couple of schemes for formal consideration and quite a few enquiries of proposed schemes.* The designs were altered to provide enclosures or alternative means of escape. No further details have been provided.

e) *Many single-storey flats.* The overall flat dimensions, open plan room dimensions, types of rooms and numbers of each type have been supplied. Salient details are:

- The travel distance to the final exit for the open plan room is 9 m.
- The travel distance to the final exit from the furthest inner room is 9 m.
- Door with door closer always on the flat entrance and doors on the bath/shower/WC room, and sometimes door to the bedroom.

f) *Three buildings containing 75 single-storey flats.* The overall flat dimensions, open plan room dimensions, types of rooms, numbers of each type and plans have been supplied. Salient details are:

- The travel distance to the final exit from the furthest inner room is 7 m.
- There are doors to the bedrooms and main entrance. Door closers are on the main entrance to the flat.

g) *100+ single-storey flats.* The overall flat dimensions, open plan room dimensions, types of rooms, numbers of each type and plans have been supplied. Salient details are:

- The travel distance to the final exit for the open plan room is 10 m.
- The travel distance to the final exit from the furthest inner room is 6 m.
- There are doors around the hallway. Door closers are on the flat entrance door only.

h) *Ten buildings containing single-storey and duplex flats.* The overall flat dimensions, open plan room dimensions, types of rooms and numbers of each type have been supplied. Salient details are:

- The travel distance to the final exit for the open plan room is 9 m.
- The travel distance to the final exit from the furthest inner room is 9 m.
- There is an enhanced fire detection system.
- There is an automatic sprinkler system.
- There are various doors, normally to bedrooms and bathrooms. Door closers are on the flat entrance door only.

i) *Four schemes at the concept stage containing single-storey flats.* The overall flat dimensions, open plan room dimensions, types of rooms and numbers of each type, the travel distance to the final exit for the open plan room and the travel distance to the final exit from the furthest inner room, and details of doors and door closers have not been supplied. Other salient details are:

- There is an enhanced fire detection system.
- There is an automatic sprinkler system.
- There are various doors, normally to bedrooms and bathrooms. Door closers are on the flat entrance door only.

j) *Six to twelve schemes containing single-storey and duplex flats.* The overall flat dimensions, open plan room dimensions, types of rooms and numbers of each type have not been supplied. Other salient details are:

- There is an enhanced fire detection system. Full automatic fire detection system to LD2 standard.
- There is an automatic residential sprinkler system.
- There are doors to the bedroom on the upper floor in the duplex apartments and on the bedrooms in the single floor. There are no door closers.
- A variety of layouts have been proposed which include single-storey, duplex and triplex units. The salient details are as follows:
  - Dimensions. Most designs have been close to code compliant travel distances. However, at least one project has extended dimensions of travel up to 23 m from the furthest point of the bedroom leading through to the open plan area and to the front door.
  - In one of the duplex proposals, the travel distance down the stair to the front door was around 9 m and the stair discharged within approximately 2 to 3 m of the flat entrance door. The kitchen was separated off at access level and therefore travel was through part of the conventional lounge area only.
  - Triplex apartments. These are not yet agreed and the respondent is advising additional engineering analysis to support the proposal. Again, there are limited travel distances and some fire separation at access level.
  - All of the projects have recommended the use of enhanced fire detection. The most significant discussion issues have centred on the potential for unwanted fire alarm signals and how this will be managed.
  - The majority of projects have included the additional provision of residential sprinklers. One project, where travel distance was very small (AD B compliant except for the location of kitchen), sprinklers were not included. For that particular project, the fire engineer looked at shielding the escape from the kitchen area from the potential radiative effects/exposure to the occupant standing near the flat entrance door making their escape. This was to demonstrate that, for the limited time near the door, the exposure to a shielded fire from the kitchen area would be acceptable.

k) *One or two four-storey buildings with single-storey and duplex flats.* The overall flat dimensions, open plan room dimensions, types of rooms and numbers of each type have been supplied. Salient details are:

- The travel distance to the final exit for the open plan room is 14 m.
- The travel distance to the final exit from the furthest inner room is 17 m.
- There is an enhanced fire detection system, BS 5389-1[19] L1.
- There is a residential sprinkler system.
- There are doors onto the bathroom and bedrooms only. There are no door closers.

l) *Twenty-five buildings.* Many examples of plans containing the overall flat dimensions, open plan room dimensions, types of rooms and numbers of each type have been supplied. The flat designs are varied but all have an enhanced fire detection system, a residential sprinkler system, and doors but no door closers. The additional salient details of each group of plans are:

- two-bedroom flat with smoke extract through a plenum ceiling
- two-bedroom maisonette/gallery
- upside-down three-bedroom maisonette
- large two-bedroom penthouse of 20 m × 16 m including balcony
- two-bedroom open layout penthouse with a travel distance to the final exit from the furthest inner room of 27 m; also, a second design of a conventional two-bedroom penthouse but the hallway not protected, giving a maximum travel distance to the final exit from of 21 m
- one-, two- and three-bedroom flats with travel distances to the final exit from the furthest inner room of 9.5 m, 9.2 m to 13 m and 12.1 m, respectively
- 13 layouts of one-, two- and three-bedroom apartments; travel distances to the final exit from the furthest inner room are 8 m to 10 m, up to 14 m and 14 m, respectively, and the travel distance to the final exit for the open plan room is 9 m in all cases
- two-level apartment with the travel distance to the final exit from the furthest inner room 15 m.

m) *Three high-rise blocks of single-storey apartments and one low-rise block.* Two examples of plan layouts for a two- and three-bedroom apartment including the overall flat dimensions, open plan room dimensions and types of rooms and numbers of each type have been supplied. Salient details are:

- The travel distance to the final exit for the open plan room is up to 12 m.
- The travel distances to the final exit from the furthest inner room are 7.5 m, 12 m, 15 m, 25 m.
- There are linked smoke alarms in all habitable rooms; heat detectors in the kitchen area are set to activate at a lower temperature than the sprinklers.
- There is a residential sprinkler system.
- There are no doors or door closers.
- Some apartments utilise sliding partitions to form a bedroom.
- There is a single escape lighting luminaire sited at low level adjacent to the flat entrance door, within the flat.
- A number of apartments have balconies, including some with wide terraces, which could be used as refuge areas.

Justifications for the fire safety designs of the open plan flats

There are various justifications for the fire safety designs of the open plan flats, according to the questionnaire respondents. These are:

- restricted travel distance(s)
- enhanced automatic fire detection system
- fire suppression system, eg automatic sprinkler system, water mist system
- smoke control system
- alternative means of escape using balconies

- fire safety engineering calculations
- computer modelling
- quantified risk analysis
- qualitative risk analysis
- an unusual interpretation of AD B (Fire safety)
- fire safety engineering arguments
- case studies
- other:
  - all doors upgraded to FD30S standard
  - international precedents
  - comparative analysis with code compliant designs
  - BRE interpretation of results of the project *Effectiveness of sprinklers in residential premises*[7] carried out by BRE for Communities and Local Government
  - reference to North American, Australian and New Zealand codes on travel distance.

Sufficiency of the existing guidance on the fire safety of open plan flats

Three respondents replied yes, the existing guidance on the fire safety of open plan flats was sufficient. The remainder of the respondents replied no, the existing guidance was not sufficient, for the following reasons:

- It only provides for small studios or galleries and does not cater for inner rooms off open plan areas, which is what developers want.
- Justification for the fire safety design of the open plan apartments has not been incorporated into AD B, BS 5588 Part 1[20] or equivalent.
- AD B guidance is limited/non-existent and the assumption is that if open plan was easily achievable with provision of enhanced detection and/or sprinklers it would have been included in 2006.
- The use of open plan flats requires careful design by competent persons and therefore each case needs to be considered individually.
- Advice is needed on the acceptability of alternatives.
- Risk analysis is not clear.
- There is no UK guidance (on how to design open plan flat layouts).
- Additional guidance with regard to freedoms and flexibilities in relation to automatic fire suppression systems is necessary.

Other comments on open plan flat layouts

The questionnaire respondents made the following comments on open plan flat layouts:

- The relevant people need to talk to developers and then put prescriptive guidance together accordingly, so that every time there is a similar scheme the need for fire-engineered designs and solutions does not repeat itself. This is very costly and time-consuming for all concerned and could be largely eradicated if appropriate prescriptive guidance were available.
- Sprinklers with enhanced AFD and fire door specifications seem to provide the answers that could be incorporated into guidance associated with open plan inner room arrangements, subject to agreed limitations.

- Where the respondent has departed from AD B, they have found the lack of guidance elsewhere wanting and sometimes contradictory. The areas they would like further guidance on are as follows:
  - Where does the travel distance in AD B come from? Is it the slowest-moving people in the community? What was the science, if any? Could it have been 15% or more? Or less?
  - When looking at equivalency, what is the contribution given by sprinklers to fast and slow fires? Can you determine an extension of travel distance? Do sprinklers give adequate means of escape or adequate means of survival?
  - Can sprinklers replace a protected escape route?
  - Enhanced AFD helps extend travel distance, but by what percentage?
  - There are differing figures for pre-movement times of anything from 5 to 15 minutes in apartments.
- Clarification/some 'official' guidance is required as developers want to build this type of layout. Other countries, eg Australia, appear to acept open plan layouts but the latest AD B which used up-to-date research material did not provide any guidance other than by omission.
- The respondent believes that no single option listed under the justifications section is adequate in and of itself. They believe that while flats with open plan layouts are still statistically low in number, a 'standard solution' contained within the AD B would be unlikely to be robust, as each development can have huge variations. On this basis, text within the AD B should perhaps be limited to providing recognition that open plan layouts can be possible only where there is sufficient burden of proof, and this should be agreed with the building control body, on a case-by-case basis.
- Where open plan flat design is proposed, it has been suggested that an engineering analysis be carried out to demonstrate that, in principle, the functional requirements of the Building Regulations are met. The main area of concern has been that even with the provision of sprinklers, eg visibility (and possibly toxicity) in the access room could make escape from the flat impractical.
- However, the opinion of the respondent has been that with the provision of enhanced detection and the added benefits of sprinkler coverage, there will be an overall increased level of safety for the occupant regardless of any state the occupier may be in (eg mobility-impaired, intoxicated). This they have felt allows designers more freedom in their design and still meets a satisfactory level of fire safety, ie the fire will be controlled and occupants warned at an earlier stage in the fire development, allowing for escape or for the occupant to remain in a place of relative safety or 'refuge'.
- Each project has been assessed on its own merits and some projects have resulted in more detailed analysis. However, the respondent notes that there is an inconsistent approach within the industry as to the work that has been required by regulators to demonstrate any compliance with the regulations.
- Each case must be treated on its own merits. However, enhanced smoke detection, suppression and possibly smoke venting should be provided.
- Most proposals are justified using single scenario deterministic methods or a case based on overseas experience.
- With the increasing emphasis on sustainable development, lifetime homes and flexible accommodation to fit these requirements, the benefits of automatic fire sprinkler systems should be emphasised. Open plan flat layouts are an example of where Building Regulations could further support and effectively protect communities, with a requirement for the inclusion of residential sprinkler systems, thus making the potentially vulnerable occupants safer from fire and smoke, while increasing the flexibility of accommodation throughout the lifetime of the occupiers.

- Aspects of discussions that the respondent had been involved with have been as follows:
  - Local authorities have expressed the view that once the recommendation for self-closers to internal doors was removed, the arguments against inner rooms vanished.
  - Fire engineers maintained that residential sprinklers allowed inner rooms as the sprinklers would control the fire, reducing temperatures and toxicity levels. One incorrectly argued that visibility was not a factor.
  - Architects maintained that an open plan layout is desired, fashionable. One added that the majority of the flats are so small that doors cannot be accommodated.
  - Inner rooms are permitted in North America, Australia and New Zealand.
- Is there a maximum travel distance from an inner room to apartment exit? If so, what is it?

6.2.6 Review of the CRISP model and relevant experimental data

The CRISP risk assessment model

CRISP is the BRE evacuation and fire spread computer model. It is a Monte Carlo model of entire fire scenarios. It incorporates a two-layer zone model of smoke flow for multiple rooms, coupled with a detailed model of human behaviour and movement. As the people move around the building, they may be exposed to toxic smoke. The risk can be expressed simply as the average number of fatalities per fire, over a sufficiently large Monte Carlo sample. The CRISP risk assessment model[9-11] is described in more detail in section 6.4 in appendix B.

Experimental data used to validate the CRISP model

CRISP has been validated using data from experimental fires in real buildings. This validation is limited to purely physical aspects such as fire growth, smoke movement, detector operation, etc. Obviously, human response to the fire environment could not be included in these experiments.

A BRE research study into the effectiveness of residential sprinklers[7] included a number of fires where televisions were burnt in the lounge of the experimental house inside the BRE Cardington Laboratory (see *Other experimental data* below). In a subsequent BRE study[21] for the ODPM (now Communities and Local Government) looking at the numbers of smoke and heat detectors required in a domestic house, CRISP was used to model these fire experiments.

However, as the experiments had aspects that were beyond control (eg differences in fire growth rate), a comparison was also made between CRISP and another zone model, CFAST.[22] CFAST has been developed by NIST in the USA over many years, and is in widespread use throughout the fire community.

In addition to attempting to simulate the experiments, comparisons between CRISP and CFAST simulations of a fire in a single room were also performed. By modelling as simple a scenario as possible, any differences between the two models should be highlighted.

It was found that CRISP and CFAST predicted similar smoke/air layer interface heights in most circumstances; there seemed to be a trend for the interface in CRISP to be slightly lower (nearer the floor) than in CFAST. Where there were significant differences, these were in many cases due to the different strategies adopted by the models to deal with situations where two stratified layers do not exist.

The temperature predictions of CRISP tended to be lower than those of CFAST. This seemed to be because of different treatment of heat losses to the compartment boundaries. Further work would be required to determine the precise differences responsible for the effect.

Given the amount of variation between experiments, it is hard to say whether CRISP or CFAST gave a 'better' match to the experimental measurements. In some cases CRISP appeared better, in other cases CFAST. The 'bottom line' is that the smoke movement and heat transfer algorithms seem reasonably valid. There may, however, be scope for improvement in the heat transfer to the compartment walls, but this is likely to be less significant than other factors leading to errors/uncertainties in CRISP.

In 2006, a series of fire experiments was performed in a block of flats in Dalmarnock, Glasgow.[23] The tests were extensively instrumented and subsequently investigated in detail. The results from the Dalmarnock tests have been used in the FireGRID study,[24] which has the objective of combining sensor information with super-real-time computer simulation of fire development, in order to predict future events such as flashover, structural failure, etc. Such information will clearly be of benefit to firefighters; prediction of smoke movement could also be of value in guiding evacuation from complex buildings, provided there are suitable means of conveying instructions to the occupants.

CRISP has been identified as a key component of the FireGRID study. It was chosen as a state-of-the-art simulation tool and also because the longer-term aims of the work include egress prediction and code parallelisation, requiring full access to source code. CRISP has been used[25] to model the first (most realistic) of the Dalmarnock fire tests. In the initial modelling, the measured heat release rate from the test was used as direct input to the CRISP model (ie CRISP did not attempt to predict the heat release rate). Agreement between the model's predictions for smoke temperature, and the experimental measurements, was very good. CRISP was then used in its Monte Carlo mode, to simulate thousands of different fire scenarios. It was demonstrated that, given a sufficiently wide range of possible values for the various parameters that govern fire growth, a reasonable match between the CRISP model and the actual fire could be found.

Work is in progress to enable the initially wide range of parameter values to be refined in the light of sensor information, so that the model does not simulate fires that are not a match to the real one. By continuing the simulations beyond the current state of the real fire, predictions of future events should be possible.

Other experimental data

BRE has carried out several studies on residential sprinklers on behalf of Communities and Local Government. One study was carried out to determine the benefits and effectiveness of sprinklers in residential accommodation. This study comprised a cost–benefit analysis, benchmark tests and an experimental programme. The study established a baseline for future comparisons and concentrated on pendent residential sprinklers. The full details of this study can be found in the report.[7]

An experimental programme, burning realistic residential fuel arrays, was conducted to examine and quantify the effectiveness of residential sprinklers, in particular to life safety in the room of fire origin. The effectiveness of the sprinklers was primarily assessed by measuring their ability to control toxicity, temperature and visibility in the fire room and connected spaces. Fractional effective dose (FED) calculations were performed using gas concentrations, gas temperatures and optical density per metre measurements taken in each test. The experimental programme comprised house and compartment fires.

Eight lounge fires were conducted inside a two-storey house with a loft conversion, with and without sprinklers. Smoke alarms were present. Fire tests were performed in a standard lounge and an open plan lounge arrangement. The effect of lounge/hallway door being open or closed, water flow rate, sprinkler orientation and sprinkler model were studied.

Twenty-nine compartment fires were conducted inside a room connected to an adjoining single-storey volume via a doorway, with and without sprinklers. Smoke alarms were present. The scenarios were unshielded, shielded, sprinklered and unsprinklered fires;

three types of lounge fires, one type of bedroom fire and one type of kitchen fire. The effects of fire room door being open or closed, compartment size, sprinkler model, sprinkler orientation and water flow rate were also studied.

The conclusions of the experimental programme were:

- For the majority of scenarios studied experimentally, the addition of residential sprinkler protection proved effective in potentially reducing casualties in the room of fire origin and connected spaces.
- Sprinkler protection was not found to be a panacea; slow growing and shielded fires can be a problem.
- Smoke alarms, fitted in the room of fire origin, responded typically in half the time required by sprinklers and well before the conditions had become life-threatening.
- Closing the door to the room of fire origin, in both sprinklered and unsprinklered cases, can be effective in keeping tenable conditions in connecting spaces.

A related, follow-on study was carried out to investigate the suitability of concealed and recessed pattern sprinklers for use in residential premises, particularly concerning their effectiveness and maintainability. The study involved the selection and characterisation of products, an experimental programme of twelve stylised and ten realistic fires, the development and evaluation of a new thermal sensitivity test and a review of maintainability issues, ie issues concerning design, installation and maintenance of concealed and recessed residential sprinkler products that might detrimentally affect their performance. The full details of this study can be found in the report.[8]

Ten realistic fires were carried out inside a suitable test room in a similar way to the previous study for pendent residential sprinklers, and the results were compared with those for the pendent residential sprinklers. Television and table fires were examined with sprinklers and with the door of the room of fire origin to the hallway open. In addition to the fire scenario, the other parameters investigated were sprinkler model (one pendent, three concealed) and recess distance (manufacturer's recommended maximum and minimum). The water flow rate of the single operating sprinkler was either 60 l/min or the manufacturer's recommended minimum if greater than 60 l/min.

The conclusions of the realistic fires part of the study were as follows:

- In the realistic experimental fires, the overall performance of concealed sprinklers was similar to the performance of the pendent sprinkler.
- The addition of concealed residential sprinkler protection proved effective in potentially saving lives in the room of fire origin for the television fires, but proved ineffective in potentially saving lives for the table fires.
- Smoke alarms fitted in the room of fire origin responded in 31%-57% of the time required by sprinklers and well before conditions had become life-threatening, and smoke alarms fitted in adjacent spaces responded in 43%-77% of the time required by sprinklers and well before conditions had become life threatening.
- Generally, the concealed sprinklers operated later and at higher temperatures than the pendent sprinklers.
- The conclusions of the whole study, including those relating to the stylised fires, the development and evaluation of the thermal sensitivity test and the review of maintainability issues are contained in the report.[8]

6.2.7 Conclusions

The conclusions of the first phase of the project are as follows:

- There is limited published information and data in the public domain that is relevant to the issues of open plan flat designs.
- The bulk of the collected information is anecdotal, obtained from BRE and steering group members' experiences and from questionnaire responses.
- Thirty questionnaires were returned, of which 15 contain some details of open plan flats. Three respondents thought existing guidance on the fire safety of open plan flats was sufficient, but the remainder wanted more advice.
- There is no uniformity of approach to open plan flat design in different countries' building codes.
- A number of qualitative arguments based on logic have been proposed to justify open plan flats.
- Evidence from fire models needs to consider all aspects of the whole system, including human behaviour. The risks of the alternative solution need to be quantified and compared with an equivalent design that satisfies the provisions of AD B.
- The BRE risk assessment model CRISP has been validated for use in domestic occupancies using experimental data and real fire incident data for human behaviour.

QUESTIONNAIRE – ASSESSING LIFE SAFETY OF OPEN PLAN FLAT LAYOUTS IN THE UK

1. Please select one of following categories, which best describes your primary role.

- Client
- Developer
- Architect
- Fire engineer
- Local authority building control officer
- Approved inspector
- Fire authority – fire prevention officer
- Builder
- Other, say what:

2. Have you or your company been involved in the design or approval of proposed designs of open plan flats in the UK?

Yes No

If the answer to question 2 is 'No', the questionnaire is finished. If Yes, please proceed to the next question.

3. Roughly, how many buildings with open plan flat layouts in the UK have you or your company dealt with?

Number of buildings

4. Whereabouts in the UK are these?

- Mainly in general locality of your business, where
- Mainly in specific location(s), where
- Randomly spread across the UK
- Other – please specify

5. Were these open plan flat designs approved?

- Yes, number
- No, number

Please provide any further details:

6. Please provide details for each of the proposed or actual designs, as follows. Please attach or enclose any plans or sketches.

a. What type of flat is it? Please tick.

- Single-storey
- Duplex (two-storey)
- Other, please state:

b. What are the overall flat dimensions (approximate)?

m, by m, by m high

c. What are the open plan room dimensions (approximate)?

m, by m, by m high

d. What are the types of rooms and numbers of each type?

No.	Room type
	Lobby/hallway, number
	Dining room, number
	Kitchen, number
	Kitchen/dining room, number
	Lounge, number
	Lounge/dining room, number
	Lounge/dining room/kitchen, number
	Bedroom, number
	Lounge/dining room/bedroom, number
	Lounge/dining room/bedroom/kitchen, number
	Bathroom/shower room/toilet, number
	Utility room, number
	Other, please state:

e. What is the travel distance to the final exit for open plan room? m

f. What is the travel distance to the final exit from furthest inner room? m

g. Is there an enhanced fire detection system?

Yes No

Please provide further details:

h. Is there a fire suppression system?

- Yes, please say what
- No

Please provide further details:

i. Are there any doors?

- Yes, please state where
- No

j. Are there any door closers?

- Yes, please state where
- No

7. What were the justifications for the fire safety designs of the open plan flats? (Please tick all that apply).

- Restricted travel distance(s)
- Enhanced automatic fire detection system
- Fire suppression system
- Smoke control system
- Alternative means of escape (eg 'kick out' panels, balconies)
- Fire safety engineering calculations
- Computer modelling
- Quantified risk analysis
- Qualitative risk analysis
- Fire safety engineering arguments
- Published literature
- Case studies
- Other, say what:

8. Do you consider that existing guidance on the fire safety of open plan flats is sufficient?

- Yes
- No, say why:

9. Are there any other comments on open plan flat layouts that you wish to make?

QUESTIONNAIRE FOR FIRE INVESTIGATORS
– ASSESSING LIFE SAFETY OF OPEN PLAN FLAT LAYOUTS IN THE UK

1. Please select one of following categories that best describes your primary role.

- ☐ Fire authority fire investigator
- ☐ Police fire investigator
- ☐ FSS
- ☐ Police SOCO
- ☐ Private fire investigator
- ☐ Other, say what:

2. Have you or your organisation been involved in the investigation of any real fires in flats with open plan layouts in the UK?

☐ Yes ☐ No

If the answer to question 2 is 'No', the questionnaire is finished. If 'Yes', please proceed to the next question.

3. Roughly, how many fires in buildings with open plan flat layouts in the UK have you or your organisation dealt with?

Number of fires

Please provide any details below:

4. Whereabouts in the UK were these?

- ☐ Mainly in general locality of your business, where
- ☐ Mainly in specific location(s), where
- ☐ Randomly spread across the UK
- ☐ Other – please specify

5. As far as you know, were these open plan flats approved by Building Control?

- ☐ Yes, number
- ☐ No, number

Please provide any further details:

6. What type of flat(s) was it/were they?

- ☐ Single-storey
- ☐ Duplex (two-storey)
- ☐ Other, please state:

Number

Please attach or enclose any plans or sketches.

7. Do you consider that existing guidance on the fire safety of open plan flats is sufficient?

- ☐ Yes
- ☐ No, please say why:

9. Are there any other comments on open plan flat layouts that you wish to make?

APPENDIX B

Details of the computer modelling study

6.3 Review and evaluation of systems identified

Evidence from fire models used to justify open plan flats needs to consider all aspects of the whole system, including human behaviour. The risks of the alternative solution need to be quantified and compared with an equivalent design that satisfies the provisions of AD B.

CRISP has been used to determine the risk levels for selected open plan flats and their equivalent AD B compliant designs.

6.4 The CRISP risk assessment model

CRISP is the BRE evacuation and fire spread computer model. It is a Monte Carlo model of entire fire scenarios.[9–11] Monte Carlo methods are experiments based on random numbers, usually produced by a computer. In this application, the Monte Carlo simulation approach models individual fire scenarios and, like an opinion poll, uses a limited but representative sample of these scenarios to infer an estimate of the risk to life arising from all possible fires. Deterministic sub-models describe the different processes and events taking place during the fire. Initial values for each run, and the outcomes of events during the scenario, can be sampled from suitable statistical distributions. Monte Carlo simulations are ideally suited to practical applications, since there is the opportunity to include a high level of detail where necessary, and complex conditional probabilities.

The sub-models representing physical 'objects' (Fig. 22) include rooms, doors, windows, sprinklers, detectors and alarms, items of furniture, hot smoke layers and people. The randomised aspects include starting conditions such as various windows and doors open or closed, the number, type and location of people within the building, the location of the fire and the type of burning item.

The basic structure of CRISP is a two-layer zone model of smoke flow for multiple rooms, coupled with a detailed model of human behaviour and movement. All the physical 'objects' are supervised by the Monte Carlo controller, making each one perform for each time step. The Monte Carlo controller also handles all the input and output, and initialisation for each run, and starts each run automatically. Functions are included to generate random numbers from any distribution. The calculations for each run are carried out iteratively, with variable time intervals to ensure the programme's efficiency, accuracy and stability.

CRISP predictions of fire and smoke behaviour have been compared with relevant available experimental data (including sprinklers), real fire incident data for human behaviour and computer simulations using other models. Satisfactory agreement has been observed.

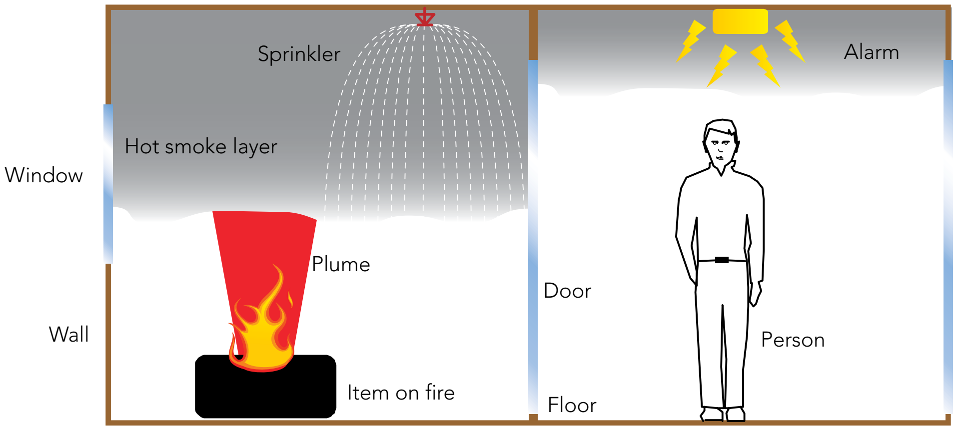


Figure 22 A pictorial representation of the primary physical 'objects' in the CRISP simulation.

As the people move around the building, they may be exposed to toxic smoke and acquire a fractional effective dose (FED). When the FED reaches 100%, the person is defined as 'dead'. The risk can be expressed simply in terms of the fraction of people originally present who achieve a FED of 100%, ie are 'dead', averaged over a sufficiently large Monte Carlo sample (Fig. 23). Alternatively, the risk can be expressed as the average number of fatalities per fire over this large sample.

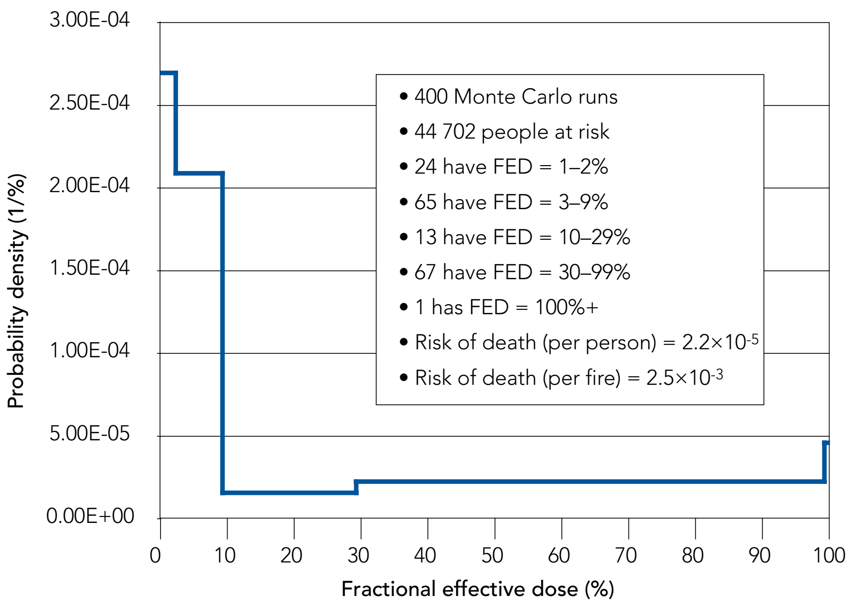


Figure 23 Example of risk calculation for a medium-sized office building.

6.5 Assumptions and data for CRISP model

6.5.1 Modelling scenarios

The scenarios selected for CRISP modelling were proposed, discussed and agreed at the second steering group meeting.

Nine cases have been modelled, in three groups of three. Each group of three is based on a similar floor plan, representing a one-bedroom flat/bedsit, a medium-sized two-bedroom flat, and a large three-bedroom flat. Within each group, there are three options, representing an AD B compliant case, an alternative case, and the alternative case plus sprinkler protection.

Not all possible designs could be considered. For example, mezzanine floors and ultra-large penthouse flats are not covered in this study.

The size of the open plan lounge is equivalent to the size of the hall and lounge for the AD B compliant comparison case.

Flat dimensions and details of layouts and active fire protection systems installed for the nine scenarios are as shown in Figures 24 to 32 and summarised in Table 4. Larger scale drawings are shown in Figures 2 to 10 in section 4.2.

Table 4

Summary of the CRISP modelling cases

Case	Description	AD B compliant or open plan	Size of footprint and ceiling height	Active protection systems present
1a	Studio (9 m travel distance)	AD B compliant	8 m × 4 m × 2.4 m high	LD3 system[3] (smoke alarm in the circulation space)
1b	One inner bedroom*	Open plan	8 m × 4 m × 2.4 m high	LD1 system[3] (smoke alarm in each room)
1c	One inner bedroom*	Open plan	8 m × 4 m × 2.4 m high	LD1 system[3] (smoke alarm in each room) plus sprinklers[4]
2a	Two bedrooms	AD B compliant	10 m × 8 m × 2.4 m high	LD3 system[3] (smoke alarm in the circulation space)
2b	Two inner bedrooms	Open plan	10 m × 8 m × 2.4 m high	LD1 system[3] (smoke alarm in each room)
2c	Two inner bedrooms	Open plan	10 m × 8 m × 2.4 m high	LD1 system[3] (smoke alarm in each room) plus sprinklers[4]
3a	Three bedrooms	AD B compliant	16 m × 12 m × 2.4 m high	LD3 system[3] (smoke alarm in the circulation space)
3b	Three inner rooms	Open plan	16 m × 12 m × 2.4 m high	LD1 system[3] (smoke alarm in each room)
3c	Three inner bedrooms	Open plan	16 m × 12 m × 2.4 m high	LD1 system[3] (smoke alarm in each room) plus sprinklers[4]

* 9 m travel distance measured to back of inner room.

Group 1

Group 1 is a one-bedroom flat or bedsit, with a footprint of 8 m × 4 m. The AD B compliant case represents a bedsit (case 1a), and the alternative has the bedroom as an 'inner room' accessed from the living room/kitchen (case 1b). There is also an alternative with additional sprinkler protection (case 1c).

Cases 1a to 1c are shown in Figures 24 to 26.

Some additional details of the geometry (not marked on the floor plans) are as follows:

- All doors have a width of 0.8 m and a height of 2.2 m.
- All windows have a width of 2 m, a sill height of 0.8 m and a soffit height of 2.2 m.
- All ceilings have a height of 2.4 m.
- 'Archways' (eg between the bedroom and lounge in case 1a) have a height of 2.4 m.

Note 1. The furniture shown in all the floor plans is merely indicative of a room's function, and is not intended to show the presence and location of specific items. Similarly, the direction of opening of the doors is not significant.
Note 2. The sprinklers and detectors shown in all the floor plans merely indicate their presence and are not intended to show the exact number or locations of specific detectors or sprinkler heads.

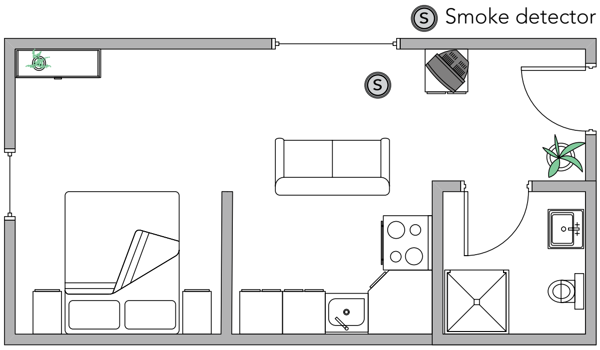


Figure 24 Case 1a.

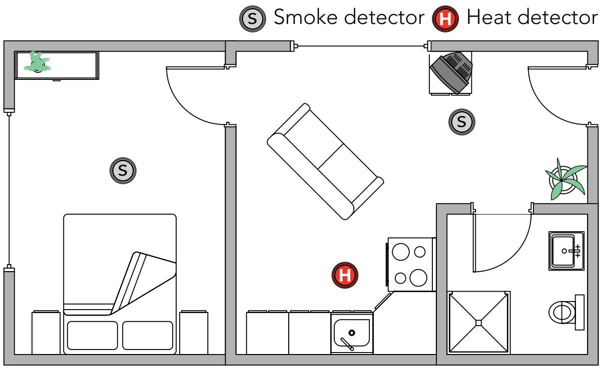


Figure 25 Case 1b.

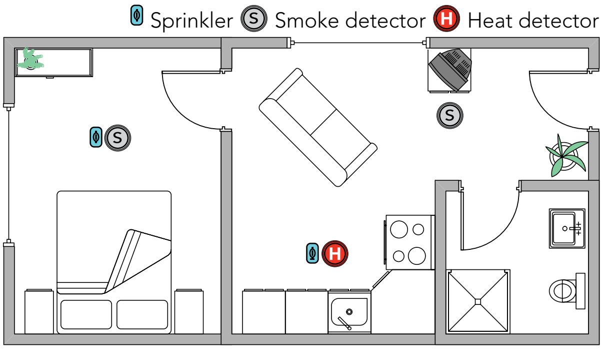


Figure 26 Case 1c.

Group 2

Group 2 is a two-bedroom flat, with a footprint of 10 m × 8 m. The AD B compliant case includes a hallway (case 2a), and the alternative has an open plan lounge with the bedrooms as 'inner rooms' accessed directly from the lounge (case 2b). There is also an alternative with additional sprinkler protection (case 2c). These cases are shown in Figures 27 to 29.

Some additional details of the geometry (not marked on the floor plans) are as follows:

- Bedroom 2 (without the en-suite shower room) has maximum dimensions 4 m × 3 m.
- All doors have a width of 0.8 m and a height of 2.2 m.
- All bedroom windows have a width of 2 m, a sill height of 0.8 m and a soffit height of 2.2 m.
- The lounge window has a width of 3 m, a sill height of 0.8 m and a soffit height of 2.2 m.
- All ceilings have a height of 2.4 m.
- 'Archways' (eg between the 'hall' and lounge in case 2b) have a height of 2.4 m.

Note. For convenience in setting up the model, the wall between the hall and the lounge was simply replaced by an archway in cases 2b and 2c. The model regards the two rooms as distinct; the consequences of doing this (rather than replacing the hall and lounge with a single larger lounge) will be subtle and are not expected to significantly affect the conclusions.

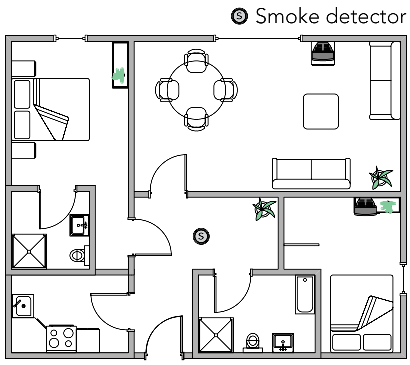


Figure 27 Case 2a.

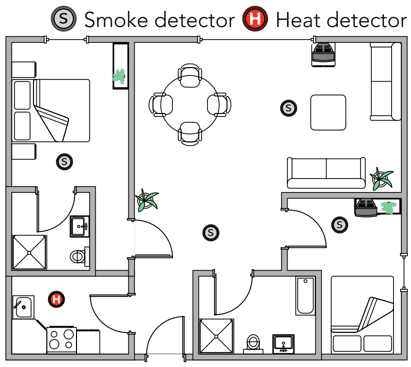


Figure 28 Case 2b.

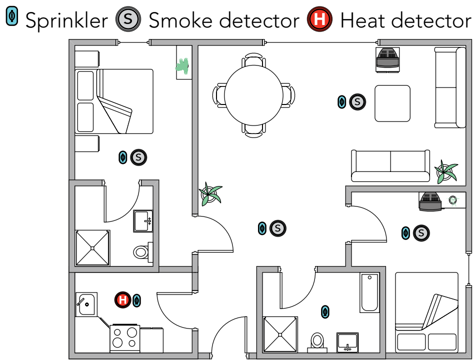


Figure 29 Case 2c.

Group 3

Group 3 is a three-bedroom flat, with a footprint of 16 m × 12 m. The AD B compliant case includes a hallway (case 3a), and the alternative has an open plan lounge with the bedrooms as 'inner rooms' accessed directly from the lounge (case 3b). There is also an alternative with additional sprinkler protection (case 3c). These cases are shown in Figures 30 to 32. They are intended to be compared against the group 2 cases to investigate the importance of travel distance.

Some additional details of the geometry (not marked on the floor plans) are as follows:

- Each bedroom has maximum dimensions of 5 m × 4 m.
- All doors have a width of 0.8 m and a height of 2.2 m.
- All windows have a width of 2 m, a sill height of 0.8 m and a soffit height of 2.2 m.
- All ceilings have a height of 2.4 m.

Note. In the cases of 3b and 3c, the hall and lounge were replaced by a single larger lounge (rather than replacing the dividing walls by archways as in group 2).

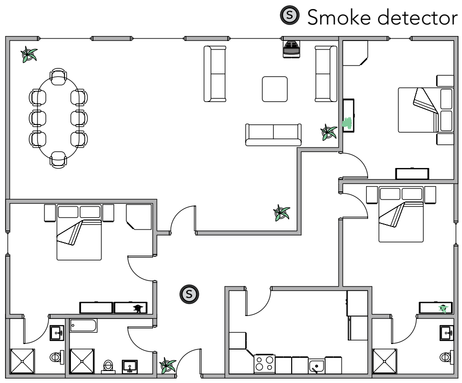


Figure 30 Case 3a.

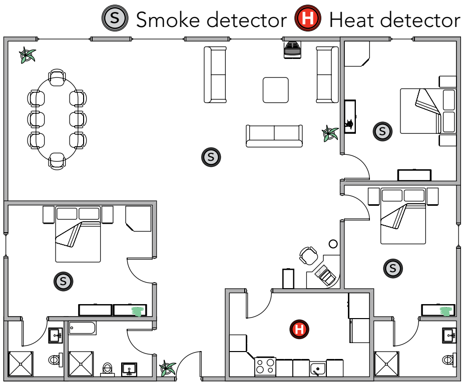


Figure 31 Case 3b.

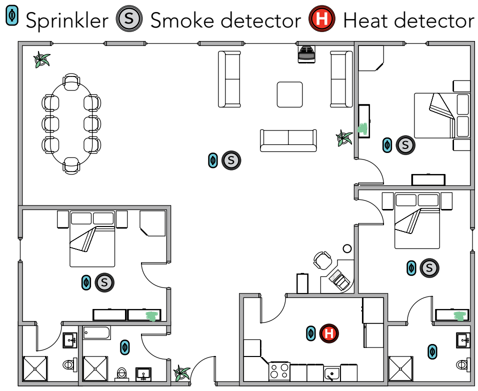


Figure 32 Case 3c.

6.5.2 Thermal properties of the walls

The thermal properties of the walls determine how quickly the wall temperature rises when it is exposed to hot smoke layers. In turn, this affects the temperature of the smoke according to the amount of heat it loses to the walls.

The properties in Table 5 apply to all the room boundaries (walls, ceilings, floors). The material properties are based on low-density concrete, taken as a 'typical' material.

Table 5

Properties of room boundaries	
Convection coefficient	0.015 kW/m^2
Density	2200 kg/m^3
Specific heat capacity	1 kJ/kg/K
Thermal conductivity	0.002 kW/K/m
Wall thickness*	0.05 m

* Internal walls – used for calculation of heat conduction from one side to the other, ie fire resistance (insulation) failure time. (External walls are regarded simply as heat sinks.)

6.5.3 Fire scenarios

CRISP determines the fire scenarios randomly. The first step in the process is to select the season of the year (affects external air temperature), time of day, room type and type of burning item. The probability of each permutation is derived from the UK Fire Statistics[26] collected by Communities and Local Government. As the data have been split into four seasons, three time periods (starting 0000, 0800 and 1600), six room types ('bedroom', 'lounge', 'kitchen', 'bathroom', 'corridor' and 'other/unknown') and seven item categories ('cooking', 'furniture', 'structure', 'waste', 'electric', 'gas/liquid' and 'other/unknown'), giving a total of 504 permutations, it is not feasible to list all the probabilities here.

If a chosen permutation cannot be simulated (eg there is no room of type 'other/unknown' defined in the building), then the permutation will be rejected and another tried, until a successful possibility is found.

Each room has a representative list of contents. One of the items that matches the chosen fire scenario (season, time, room type and item type) is ignited. The list of rooms, types, and their contents is given in Table 6.

Table 6

List of rooms, types and their contents

Room type	Item names
'bathroom'	'curtains', 'struct', 'electric', 'roomfire'
'bedroom'	'dbl_bed',* 'sgl_bed',† 'sgl_bed',‡ 'curtains', 'struct', 'clothes', 'wastebin', 'tv', 'electric', 'roomfire'
'hall'	'struct', 'electric', 'solvents', 'roomfire'
'kitchen'	'chip_pan', 'curtains', 'struct', 'wastebin', 'electric', 'solvents', 'roomfire'
'lounge'	'sofa', 'armchair', 'armchair',§ 'curtains', 'struct', 'wastebin', 'papers', 'tv', 'electric', 'roomfire'

Notes:

* Only in the main bedroom.

† In bedrooms other than the main bedroom.

‡ Bedroom 2 in the three-bedroom flat has two sgl_bed items; see Note § for how this affects the probability of choice of fire scenario.

§ Duplicating the armchair in the list of contents for the lounge means it is twice as likely to be chosen as other types of furniture (such as sofa or curtains).

The item type determines how rapidly the fire grows, how long it burns, the yields of various products, etc.

The behaviour of each burning item is governed by a number of parameters, which affect not only how it burns 'in the open', but also the effects of enhanced radiative feedback (ie from the hot smoke layer as well as the flame cone) and reduced oxygen concentration (that results from burning the fire within a room with limited oxygen supply). The equations that describe the behaviour are discussed in the CRISP manual.[11]

The 'roomfire' (type = fullroom) item has been included to simulate cases of fire spread between items that do not require flashover to occur, but instead rely on other effects such as localised radiative heat transfer, direct flame impingement, burning brands, etc. Each time a fire starts, CRISP checks to see if non-flashover fire spread occurs. The probabilities depend on the room type and are derived from the UK Fire Statistics. The probabilities are given in Table 7.

Table 7

Probability of fire spread

Room type	Fire spread probability
Bathroom	0.20
Bedroom	0.23
Hallway	0.16
Kitchen	0.07
Lounge	0.23

A full-room fire will continue to grow until the fire area is 80% of the room floor area. The amount of fuel available is calculated assuming that the fire load density follows a log-normal distribution[27] with a mean of 718 mJ/m^2 and standard deviation of 215 mJ/m^2.

6.5.4 Ventilation

The dimensions of the doors and windows have been given along with other details of the geometry above. However, even if a door or window is nominally closed, there may be gaps for smoke to leak through. There are three possible leakage paths (top, side and bottom of the door/window [assumed rectangular]), as follows:

- window – top 5 mm, side 2 mm, bottom 3 mm
- door – top 5 mm, side 10 mm, bottom 10 mm.

Archways do not have leaks because they are always fully open.

The probabilities of doors being open or closed are based on observations of domestic properties.[9, 10, 28] The probabilities depend on whether it is day (defined here as 0900–2130) or night, and the types of rooms that are linked.

Table 8

Probabilities of doors being opened or closed in the day and at night

Room type 1	Room type 2	Probability (shut|day)	Probability (shut|night)
Bathroom	Any	90%	90%
Bedroom	Not bathroom	30%	50%
Hall	Kitchen/lounge	20%	40%
Kitchen	Lounge	20%	40%

Windows, and doors to the 'outside' were assumed to always be shut.

No doors were fitted with self-closers.

Windows were assumed to crack when exposed to smoke above 90°C, when 0%–10% of the area would fall out. Further failure occurs between 250°C–350°C (a constant temperature for all glass in a particular simulation) when between 30%–70% of the area would fall out (different for each opening). Total failure (100% fall out) occurs when the temperature (for all glass in a particular simulation) is between 400°C–600°C. A cracking or breaking window makes a noise of 70 dB,[29] almost certain to alert an awake person, and rouse many sleepers too.

The flats were all assumed to be at ground level, ie no contribution from stack effects to the movement of smoke once the window(s) have failed. Wind pressure effects were also ignored.

Neither automatically opening vents (AOVs) nor mechanical smoke ventilation were considered in this study.

6.5.5 Detection, alarm and suppression (sprinklers)

Various types of detectors may be located within the building. The precise position within a room is not specified – it is assumed to be appropriate for each detector type (eg an ionisation detector will be at the highest point in the ceiling, so will be exposed to a smoke layer as soon as it forms).

Four parameters are common to all detector types. These are room ID, link zone ID, failure probability (assumed 0% for the purposes of this study), and noise output, (taken as 90 dB(A)). Link zone is an arbitrary integer; detectors with the same link zone ID will all make a noise as soon as one detector in the link zone is activated. However, a detector with a zone of 0 (zero) is unlinked.

Ionisation detectors are assumed to have a response that is correlated with the light extinction coefficient of the smoke layer: when the extinction coefficient exceeds the threshold for the detector, the alarm sounds. The light extinction coefficient required for activation is 0.23 m^{-1} (ie an optical density of 0.1 m^{-1}).[30]

Heat rise detectors activate when the sensor head temperature passes the threshold value. The head temperature, θ_h, is calculated from the smoke temperature, θ_s, at each time step of the simulation.[31]

$$\dot{\theta}_h = \frac{v_c^{0.5}}{RTI}(\theta_s - \theta_h) - \frac{C}{RTI}\theta_h \qquad \theta_h = \int_0^t \dot{\theta}_h . dt + \theta_h (t = 0)$$

CRISP does not calculate ceiling jet parameters, so a default value of 2 $m.s^{-1}$ is used for the ceiling jet velocity v_c. The other parameters assumed for the heat detectors in this study were a detector element temperature rise required for activation (36 K), response time index (RTI) (10 $m^{½}.s^{½}$) and conduction loss parameter (C) (0 $m^{½}.s^{-½}$).

Sprinkler operation is calculated using the same equations as heat rise detectors, with appropriate values for the activation temperature, conduction loss parameter (C) and response time index (RTI). These values are: detector element temperature rise required for activation (48K), response time index (50 $m^{½}.s^{½}$), conduction loss parameter (0 $m^{½}.s^{-½}$).

It has been assumed that sprinklers will always operate (provided the sprinkler head reaches its activation temperature) and will always extinguish the fire once they have operated. While this is optimistic, it is likely not to be too unrealistic. Correctly maintained sprinkler systems have a very high reliability. Estimates vary, but the reliability will almost certainly be better than 90%. Sprinklers should at least prevent a fire from growing larger even if they do not succeed in extinguishing it once they have activated.

If people hear a noise (either an alarm, or glass breaking) then they will react. People who are awake will almost certainly hear something, as their auditory threshold is only 20 dB(A). Sleeping people are harder to rouse; they require a noise exceeding a threshold that is Normally distributed N(75, 9.5) dB(A).[32] Noise can be attenuated between its source and the person trying to hear it. Noise from an adjoining room is attenuated by 7 dB, from a more distant room by 10 dB, and by an additional 20 dB by a closed door.

6.5.6 Human behaviour

People are assumed to adopt distinct behavioural roles, either naturally or because of training. Their behaviour can be described in terms of actions, which may be abandoned and substituted by new ones, depending on the state of the environment (see Table 9, section 6.5.7). Rational decisions are made based on current knowledge (which may be limited and/or incorrect). People never 'panic' (in real life, 'panic' behaviour is actually extremely rare).

The key concept behind the behavioural rules is that of an 'action',[33] which firstly requires the person to go somewhere, and then to do something. The destination may of course be the same as the person's current room, so they do not have to move. The 'do something' part of the action is represented by a period of time for which the person has to wait before the action is considered complete. On completion, various things may happen depending on what the action was (eg on completing a 'warn' action, everybody in the room will be alerted).

The model attempts to calculate 'pre-movement time' (rather than use an empirical distribution) in terms of the time delays associated with various actions performed by the occupants in response to the early fire cues. The occupants may perform a number of actions (eg investigate, warn others) before actually starting to escape (thus the term 'pre-movement time' is not strictly accurate). If the occupant's 'pre-movement' actions do not actually require him to move, then all these actions can be lumped into a single delay in reacting to the alarm.

CRISP chooses the destination automatically according to the action being performed, eg an 'investigate' action has the fire origin as the destination, a 'rescue' action has a dependent or unconscious person, and so on. The delay time is defined by this data file. It may be Normally or Log-Normally distributed. The maximum degree of difficulty (DOD) allowed for the route to the destination is also defined by this file. As the room tenability worsens, some actions may no longer be possible because a route with a low enough DOD no longer exists. The final action parameter defined in this file is the urgency, which determines how the action is perceived by others.

The allowed DOD refers to the severity of conditions (on a 0 to 5 scale; 5 is worst) that may be experienced before the action is abandoned. The urgency level determines how other people regard the person performing the action (0 = normal, 1= situation under control, 2 = time to get out). On each time step of the model, conditions relevant to the current action are tested, and if one is true, the associated new action is attempted. For any condition, there may be up to four possible new actions, with different probabilities.

Parameters of each action are independent of the role/occupation of the person performing the action. See Table 10 section 6.5.8.

The action may not be completed, before something happens that requires a new action to be started. The behavioural rules list the conditions which affect each action in the rule set. One of the more widely applicable conditions is No_route, which usually arises because thick smoke prevents the person from getting to their destination. For example, a person investigating an alarm would head towards the room of fire origin, but if they encountered thick smoke they might decide to escape at once. Actually, the way the model works, the person may try actions such as Warn_household and Rescue, but if both of these are also affected by the No_route condition, the net effect is to go directly from Investigate to Escape. (The escape route might require them to move through the smoke anyway.)

6.5.7 Behaviour rules

Table 9

Behaviour rules

Current action	IF {condition} THEN…	New action
Asleep	Complete	Wake_up
	Alerted	Wake_up
Await_rescue (D)	Complete	Warn_household
Escape (F,L)	Complete	Safe
	No_route	Trapped
Fight_fire (L)	Fire_out	Warn_household
	Complete	Go_to_water
	No_route	Warn_household
Go_to_water (L)	Fire_out	Warn_household
	Complete	Fight_fire
	No_route	Warn_household
Investigate (F,L)	Complete	Go_to_water (L)
		Warn_household (F)
	No_route	Warn_household
	Seen_fire	Warn_household
Leave_room	Cannot_leave	Trapped
	Complete	Previous action
Reacting	Complete	Investigate (F,L)
		Warn_household (D)
	No_route	Investigate (F,L)
		Warn_household (D)
	Has_reacted	Investigate (F,L)
		Warn_household (D)
Rescue (F,L)	Complete	Escape
	Target_moved	Rescue
	Target_assisted	Rescue
	No_route	Escape
Safe	Complete	Warn_household (L)
		Warn_neighbour (F)
		Safe (D)
Trapped	Complete	Waiting
Unconscious	Complete	Unconscious
Waiting	Complete	Waiting
	Senior_alerted (D)	Await_rescue
	Realerted (D,F)	Warn_household
	Alerted	Reacting
Wake_up	Complete	Waiting
Warn_household	Seniors_away (D)	Await_rescue
	Senior_alerted (D)	Await_rescue
	Complete	Warn_household
	Target_moved	Warn_household
	Target_alerted	Warn_household (F,L)
		Waiting (D)
	Target_to_warn	Warn_household
	No_route	Rescue (F,L)
		Trapped (D)
Warn_neighbour (F)	Complete	Warn_household
	Seen_neighbour	Warn_household
	Seniors_away	Warn_household

Key: D Dependent; F Follower; L Leader

Some actions, conditions, or new actions are only applicable to certain behavioural roles, indicated (L) for leaders, (F) for followers (or 'led') and (D) for dependents. All people are either Asleep or Waiting when the fire starts. They then follow the above rules to see what they do next, and when. Note that the conditions are tested in the order in which they are listed. Therefore, someone who is Waiting checks first to see if they have been re-alerted before checking if they have been alerted – this stops them wasting time with the reaction delay. It also means they go straight to Warn_household rather than Investigate beforehand.

Some action sequences may appear to set up an 'infinite loop'. This is deliberate. At each stage of the loop there will be a time delay while the action is completed. The loop will only be broken when a suitable condition arises to trigger a different sequence of actions.

Some actions (Leave_room and Unconscious) have 'hardwired' initiating conditions; eg Unconscious starts when a person's FED exceeds 100%.

Behavioural actions and conditions are explained in detail in the CRISP manual.[11]

6.5.8 Behaviour parameters

Table 10

Behaviour parameters

Action	Delay time (s)		Allowed DOD	Urgency
	Mean	Standard deviation		
Asleep	9999	0	9	0
Await_rescue	200	0	4	2
Escape	0	0	4	3
Fight_fire	15	5	2	1
Go_to_water	25	10	2	1
Investigate	5	5	2	1
Leave_room	5	5	9	3
Reacting	20	10	4	0
Rescue	30	15	4	2
Safe	30	15	9	2
Trapped	5	0	9	3
Unconscious	9999	0	9	3
Waiting	9999	0	4	0
Wake_up	60	20	9	0
Warn_household	5	5	3	2
Warn_neighbour	300	60	3	2

An action requires a person to go somewhere (which may be their existing location) and then wait for the specified delay period. In this study, the delays are all Normally distributed (or constant, if the standard deviation is zero). The allowed DOD parameter is primarily an upper limit to the amount of smoke that can be encountered before a No_route condition applies. Table 11 shows the conditions that define different tenability levels 1 … 5, which in turn determine the degree of difficulty for a route passing through these conditions. The Urgency level affects how someone's action is perceived by other people. More details are provided in the CRISP manual.[11]

Some behavioural parameters, eg time to wake up (Wake_up) and time to react (Reacting), could have a significant effect on the results. A sensitivity study was therefore recommended, the results of which can be seen in section 6.8.

A tenability level is set whenever any of the above thresholds are exceeded. Conditions will be determined by either the hot or the cold layer (except heat flux, which is only set by the hot layer), depending on where the smoke/air interface is relative to a standard head height of 1.7 m.[33]

Table 11

Conditions affecting tenability level and degree of difficulty (DOD)

Tenability level	Heat flux ($kW.m^{-2}$)	Optical density (m^{-1})	Temperature rise (K)	Carbon dioxide concentration (ppm)
1	0.5	0.01	20	2640
2	1.5	0.03	40	6600
3	2.5	0.08	80	17 400
4	5.0	0.25	150	31 200
5	15.0	0.50	250	42 000

6.5.9 Toxic dose

As the people move around, they are exposed to smoke and acquire a fractional effective dose (FED). When the FED reaches 100%, the person is defined 'dead'. The risk is expressed simply in terms of the fraction of people originally present who become 'dead', averaged over a sufficiently large Monte Carlo sample.

Purser's equations[12] have been used for the calculation of uptake rates, recast slightly (because CRISP uses mass concentrations rather than volume, and units of time are seconds rather than minutes). It has been assumed that each person has their own relative susceptibility to carbon monoxide poisoning. Rather than a fixed threshold of 100% required for death, it should be described by a Normal distribution N(100%, 14%). However, for convenience in post-processing the uptake rates are adjusted instead, and the threshold is kept constant (ie FED = 100% now refers to 100% of each individual's tolerance).

6.5.10 Building population

Each person is assigned a basic 'population member' type – in this case, either adult, elderly or child. This then affects the probability of the person's occupation type and/or behavioural role, as shown in the probability tree in Figure 33.

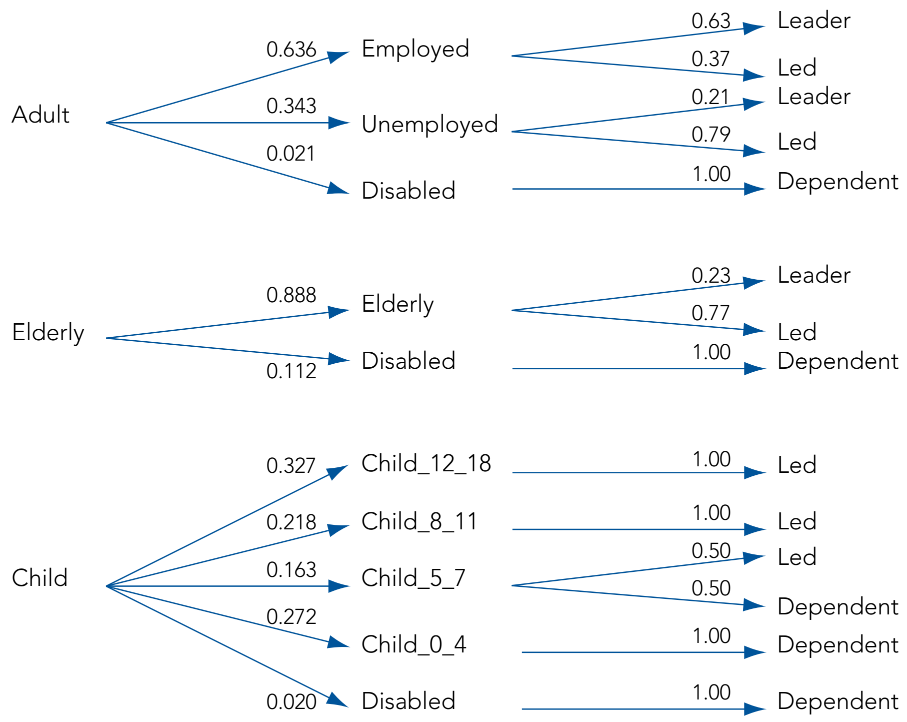


Figure 33 Probability tree to determine occupation types (first level of branching) and behavioural roles (second level of branching).

The 'family' is the basic unit of a building population. It may actually represent some form of affiliation between its members, or else simply be a convenient way of expressing the numbers of people present. The 'family profile' is a probabilistic description of the numbers of each population member type within the family. Each family has a number of possible profiles, with one selected at random according to the respective probabilities. The actual numbers of each member type associated with the chosen profile are then selected randomly, from a uniform distribution between the minimum and maximum numbers specified.

The basic family type is chosen from a list of the most common combinations, derived from census surveys.[34] Relative probabilities for the different family types in different flats were derived from the statistics for all dwellings. The basic assumption is that the 'bedroom standard' remains a constant (ie larger dwellings tend to be occupied by larger families). The procedure is quite involved, and it is beyond the scope of this report to go into details. The results are shown in Tables 12 to 19, with each row of the tables constituting a 'family profile'. Note that each flat size has a different range of profiles because the number of bedrooms varies.

Table 12

One-bedroom flat/bedsit: family types and probabilities

Family ID	Composition	Probability	Family ID	Composition	Probability
1	1 adult	0.1161	13	2 adults, 1 child	0.0417
2	1 elderly	0.2758	13a	+ 1 adult	0.0001
3	1 adult, 1 elderly	0.0357	13b	+ 1 elderly	0.0002
4	2 elderly	0.1506	13d	+ 2 elderly	0.0001
5	2 adults	0.2867	13e	+ 2 adults	0.0002
6	3 adults	0.0237	14	2 adults, 2 children	0.0358
7	4 adults	0.0070	14a	+ 1 adult	0.0001
10	1 adult, 1 child	0.0107	14b	+ 1 elderly	0.0001
10a	+ 1 adult	0.0001	14d	+ 2 elderly	0.0001
10d	+ 2 elderly	0.0001	14e	+ 2 adults	0.0001
10e	+ 2 adults	0.0002	15	2 adults, 3 children	0.0068
11	1 adult, 2 children	0.0055	16	2 adults, 4 children	0.0011
11b	+ 1 elderly	0.0001			
11e	+ 2 adults	0.0001			
12	1 adult, 3 children	0.0013			

Table 13

Two-bedroom flat: family types and probabilities

Family ID	Composition	Probability	Family ID	Composition	Probability
1	1 adult	0.0652	12	1 adult, 3 children	0.0037
2	1 elderly	0.1548	12a	+ 1 adult	0.0001
3	1 adult, 1 elderly	0.1122	12b	+ 1 elderly	0.0002
4	2 elderly	0.0845	12d	+ 2 elderly	0.0001
5	2 adults	0.1609	12e	+ 2 adults	0.0002
6	3 adults	0.0744	13	2 adults, 1 child	0.1311
7	4 adults	0.0210	13a	+ 1 adult	0.0002
8	5 adults	0.0081	13b	+ 1 elderly	0.0005
10	1 adult, 1 child	0.0270	13c	+ 1 adult, 1 elderly	0.0002
10a	+ 1 adult	0.0002	13d	+ 2 elderly	0.0003
10b	+ 1 elderly	0.0001	13e	+ 2 adults	0.0006
10c	+ 1 adult, 1 elderly	0.0003	14	2 adults, 2 children	0.1114
10d	+ 2 elderly	0.0003	14a	+ 1 adult	0.0002
10e	+ 2 adults	0.0005	14b	+ 1 elderly	0.0005
11	1 adult, 2 children	0.0140	14c	+ 1 adult, 1 elderly	0.0002

Table 13 (contd)

Two-bedroom flat: family types and probabilities

Family ID	Composition	Probability	Family ID	Composition	Probability
11a	+ 1 adult	0.0001	14d	+ 2 elderly	0.0003
11b	+ 1 elderly	0.0003	14e	+ 2 adults	0.0006
11c	+ 1 adult, 1 elderly	0.0001	15	2 adults, 3 children	0.0201
11d	+ 2 elderly	0.0002	15a	+ 1 adult	0.0001
11e	+ 2 adults	0.0003	15b	+ 1 elderly	0.0002
			15d	+ 2 elderly	0.0001
			15e	+ 2 adults	0.0002
			16	2 adults, 4 children	0.0046

Table 14

Three-bedroom flat: family types and probabilities

Family ID	Composition	Probability	Family ID	Composition	Probability
1	1 adult	0.0158	13	2 adults, 1 child	0.1292
2	1 elderly	0.0376	13a	+ 1 adult	0.0013
3	1 adult, 1 elderly	0.1105	13b	+ 1 elderly	0.0029
4	2 elderly	0.0205	13c	+ 1 adult, 1 elderly	0.0012
5	2 adults	0.0391	13d	+ 2 elderly	0.0017
6	3 adults	0.0733	13e	+ 2 adults	0.0030
7	4 adults	0.1156	14	2 adults, 2 children	0.1902
8	5 adults	0.0423	14a	+ 1 adult	0.0013
9	6 adults	0.0089	14b	+ 1 elderly	0.0029
10	1 adult, 1 child	0.0113	14c	+ 1 adult, 1 elderly	0.0010
10a	+ 1 adult	0.0009	14d	+ 2 elderly	0.0016
10b	+ 1 elderly	0.0003	14e	+ 2 adults	0.0030
10c	+ 1 adult, 1 elderly	0.0014	15	2 adults, 3 children	0.1109
10d	+ 2 elderly	0.0011	15a	+ 1 adult	0.0004
10e	+ 2 adults	0.0021	15b	+ 1 elderly	0.0009
11	1 adult, 2 children	0.0153	15c	+ 1 adult, 1 elderly	0.0002
11a	+ 1 adult	0.0006	15d	+ 2 elderly	0.0005
11b	+ 1 elderly	0.0015	15e	+ 2 adults	0.0010
11c	+ 1 adult, 1 elderly	0.0011	16	2 adults, 4 children	0.0249
11d	+ 2 elderly	0.0008	16a	+ 1 adult	0.0001
11e	+ 2 adults	0.0015	16b	+ 1 elderly	0.0002
12	1 adult, 3 children	0.0163	16d	+ 2 elderly	0.0001
12a	+ 1 adult	0.0004	16e	+ 2 adults	0.0002
12b	+ 1 elderly	0.0009			
12c	+ 1 adult, 1 elderly	0.0007			
12d	+ 2 elderly	0.0005			
12e	+ 2 adults	0.0010			

The assumption that all dwellings follow the same distribution of 'bedroom standard' may not be correct. For example, if the three-bedroom flat is regarded as a 'luxury apartment', it is more likely that it will be occupied by small (wealthy) families, with children relatively unlikely.

The 'occupation' data are primarily concerned with a person's location probabilities as a function of time, and whether they are initially awake or asleep. CRISP firstly uses the fire start time (determined by the choice of scenario) to select the relevant portion of the data for this person. It is determined whether the person is initially awake or asleep.

If the person is awake, the next step is to see if they are in the building, or if they are absent. If they are inside, the type of room they start in is chosen at random based on the probabilities given in this file. If the person is initially asleep, a different set of probabilities is used to determine the type of room they may be found in. A list of rooms of the appropriate type is generated and one of these is selected at random. If no rooms of the appropriate type exist in the building, then CRISP repeats the random choice of room type until it is successful.

Other data that depend on a person's occupation type are their movement speed (Normally or Log-Normally distributed) and their head height (also Normally or Log-Normally distributed). A person's sex is not explicit within the model.

Table 15

Probability of being asleep, for different time periods

Occupation	Start of time period					
	0000	0400	0800	1200	1600	2000
Adult_E	1.00	0.95	0.00	0.00	0.00	0.25
Adult_UE	1.00	0.95	0.00	0.00	0.00	0.30
Bedridden	1.00	0.75	0.10	0.15	0.10	0.75
Child_0_4	1.00	1.00	0.25	0.10	0.40	1.00
Child_5_7	1.00	1.00	0.10	0.00	0.40	1.00
Child_8_11	1.00	1.00	0.00	0.00	0.15	0.90
Child_12_18	1.00	0.95	0.05	0.00	0.00	0.50
Elderly	1.00	0.75	0.05	0.10	0.05	0.50

Table 16

Probability of being inside if awake, for different time periods

Occupation	Start of time period					
	0000	0400	0800	1200	1600	2000
Adult_E	1.00	1.00	0.00	0.00	0.40	0.80
Adult_UE	1.00	1.00	0.70	0.70	0.85	0.80
Bedridden	1.00	1.00	1.00	1.00	1.00	1.00
Child_0_4	1.00	1.00	0.85	0.95	1.00	1.00
Child_5_7	1.00	1.00	0.00	0.40	0.95	1.00
Child_8_11	1.00	1.00	0.00	0.05	0.80	1.00
Child_12_18	1.00	1.00	0.00	0.00	0.60	0.85
Elderly	1.00	1.00	0.85	0.85	0.95	1.00

Table 17

Probability of being in different locations if inside and awake

Occupation	Bedroom	Lounge	Kitchen
Adult_E	0.20	0.80	0.00
Adult_UE	0.30	0.60	0.10
Bedridden	0.90	0.10	0.00
Child_0_4	0.20	0.80	0.00
Child_5_7	0.35	0.65	0.00
Child_8_11	0.45	0.55	0.00
Child_12_18	0.65	0.35	0.00
Elderly	0.25	0.75	0.00

Table 18

Probability of being in different locations if asleep			
Occupation	Bedroom	Lounge	Kitchen
Adult_E	0.97	0.03	0.00
Adult_UE	0.97	0.03	0.00
Bedridden	0.97	0.03	0.00
Child_0_4	0.97	0.03	0.00
Child_5_7	0.50	0.50	0.00
Child_8_11	0.50	0.50	0.00
Child_12_18	0.50	0.50	0.00
Elderly	0.50	0.50	0.00

Table 19

Head height and walking speed		
Occupation	Height (m)	Speed ($m.s^{-1}$)
Adult_E	N(1.69, 0.16)	N(1.20, 0.12)
Adult_UE	N(1.69, 0.16)	N(1.20, 0.12)
Bedridden	N(1.50, 0.25)	0.00
Child_0_4	N(0.50, 0.06)	0.00
Child_5_7	N(1.10, 0.06)	N(0.80, 0.15)
Child_8_11	N(1.40, 0.08)	N(1.00, 0.15)
Child_12_18	N(1.54, 0.24)	N(1.10, 0.15)
Elderly	N(1.54, 0.16)	N(0.30, 0.10)

Note: These are Normal distributions.

6.6 Results

Figure 34 summarises the main results. It shows the risks from fire in the nine cases examined. These risks are expressed in terms of the average number of people per fire who acquire various levels of toxic dose (FED).

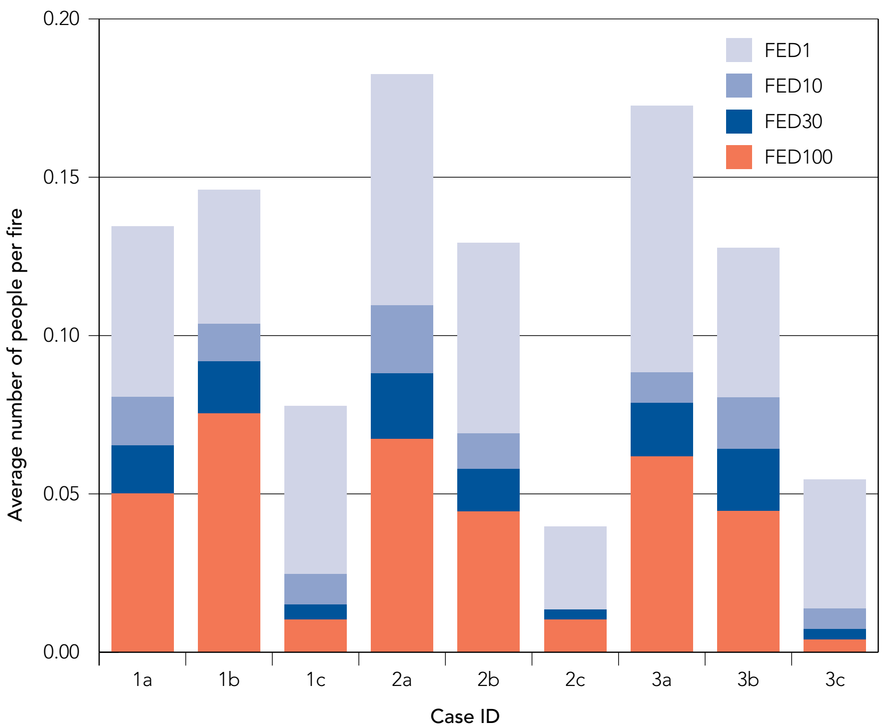


Figure 34 Main results. Risk of death or different levels of injury for each case.

Many other graphs have been plotted from the CRISP results. The CD-Rom contains these supplementary graphs which are provided for completeness.

Table 20 gives the numerical values of the averages, per fire, together with an indication of the uncertainty (the error on the mean is ± one standard deviation, although note that this is just the variation in the model's outputs, and does not include any systematic uncertainties arising from the model itself). The numbers are the averages, per fire.

Table 20

Summary of results for cases 1a to 3c

	Case 1a			Case 1b			Case 1c		
	mean		error on mean	mean		error on mean	mean		error on mean
Number_at_risk	1.31	+/-	0.02	1.33	+/-	0.02	1.37	+/-	0.03
Number_dependents	0.14	+/-	0.01	0.14	+/-	0.01	0.16	+/-	0.01
Number_immobile	0.14	+/-	0.01	0.13	+/-	0.01	0.17	+/-	0.01
Number_inside	0.150	+/-	0.013	0.139	+/-	0.013	0.163	+/-	0.014
Number_FED1	0.134	+/-	0.012	0.146	+/-	0.012	0.078	+/-	0.009
Number_FED	0.109	+/-	0.010	0.127	+/-	0.012	0.047	+/-	0.007
Number_FED10	0.081	+/-	0.009	0.104	+/-	0.011	0.025	+/-	0.005
Number_FED30	0.065	+/-	0.008	0.092	+/-	0.010	0.015	+/-	0.003
Number_FED100	0.050	+/-	0.007	0.075	+/-	0.009	0.010	+/-	0.003
Weighted Average FED	6.44	+/-	0.72	9.10	+/-	0.97	1.67	+/-	0.25
	Case 2a			Case 2b			Case 2c		
	mean		error on mean	mean		error on mean	mean		error on mean
Number_at_risk	1.69	+/-	0.03	1.68	+/-	0.03	1.63	+/-	0.03
Number_dependents	0.26	+/-	0.01	0.24	+/-	0.01	0.26	+/-	0.01
Number_immobile	0.23	+/-	0.01	0.23	+/-	0.01	0.23	+/-	0.01
Number_inside	0.320	+/-	0.022	0.183	+/-	0.017	0.280	+/-	0.020
Number_FED1	0.183	+/-	0.015	0.129	+/-	0.012	0.040	+/-	0.006
Number_FED	0.144	+/-	0.014	0.090	+/-	0.009	0.021	+/-	0.004
Number_FED10	0.110	+/-	0.012	0.069	+/-	0.008	0.013	+/-	0.003
Number_FED30	0.088	+/-	0.010	0.058	+/-	0.007	0.013	+/-	0.003
Number_FED100	0.067	+/-	0.009	0.044	+/-	0.006	0.010	+/-	0.003
Weighted Average FED	8.63	+/-	0.99	5.53	+/-	0.68	1.38	+/-	0.31
	Case 3a			Case 3b			Case 3c		
	mean		error on mean	mean		error on mean	mean		error on mean
Number_at_risk	2.36	+/-	0.04	2.42	+/-	0.04	2.39	+/-	0.04
Number_dependents	0.42	+/-	0.02	0.46	+/-	0.02	0.44	+/-	0.02
Number_immobile	0.35	+/-	0.02	0.39	+/-	0.02	0.37	+/-	0.02
Number_inside	0.473	+/-	0.031	0.250	+/-	0.023	0.321	+/-	0.027
Number_FED1	0.173	+/-	0.017	0.128	+/-	0.013	0.054	+/-	0.008
Number_FED	0.137	+/-	0.014	0.107	+/-	0.011	0.032	+/-	0.006
Number_FED10	0.088	+/-	0.011	0.080	+/-	0.010	0.014	+/-	0.004
Number_FED30	0.079	+/-	0.011	0.064	+/-	0.009	0.007	+/-	0.003
Number_FED100	0.062	+/-	0.010	0.045	+/-	0.008	0.004	+/-	0.002
Weighted Average FED	7.63	+/-	1.00	6.16	+/-	0.82	0.85	+/-	0.21

As the family size increases, so does the number of dependent members (and a subset of these, immobile dependents). 'Number_at_risk' refers to people at the start of the fire; 'Number_inside' is those people who have not left the flat, for whatever reason (but not because they are dead), by the time the simulation ends. 'Number_FED1' is the average number of people with FED>1%, etc. The 'Weighted Average FED' is the average, per fire, of the sum of the dose received by all the people at risk from that fire. As shown in a previous paper,[10] this is a good measure for the overall risk since it is strongly correlated with the number of deaths but has a lower fractional error.

6.7 Discussion of main results

For each of the nine cases, Figure 34 shows the average number of people per fire whose FED is >1%, >10%, >30%, and 100%. These represent progressively more severe levels of exposure; when FED reaches 100% the person is defined dead. With a FED of >10%, a person would almost certainly be recorded as an 'injury' in the fire statistics for a real fire. A FED of ~1% might be sufficient for a person to be sent to hospital for a precautionary check. Note that people with FED>10% form a subset of people with FED>1%, people with FED>30% form a subset of people with FED>10%, etc.

The size of flat does not seem to make a great deal of difference to the results. Even for the three-bedroom flat the maximum travel distance when escaping is unlikely to exceed 20 m, so provided that the flat is not totally smoke-logged (ie in most cases, the optical density needs to exceed 0.5 m^{-1} (visibility distance 2 m or less) *and* the smoke layer needs to be less than 1.7 m above floor height), the movement time will be ~20s. This is not the only factor, of course; it has been assumed in this study that larger flats tend to have larger families occupying them (ie more people potentially at risk), but on the other hand there is a larger volume so the smoke will be more diluted and it will take longer for the flat to become smoke-logged.

In the one-bedroom flat (cases 1a,1b and 1c) the risk is highest in case 1b, where the bedroom is separate from the rest of the flat (inner room configuration). It seems likely that the compartmentation within the flat is concentrating the smoke within the area of fire origin, and this effect is greater than the benefit of an increased provision of alarms in case 1b compared with case 1a.

In the two-bedroom and three-bedroom flats, cases 2a and 3a have the bedrooms accessed via a hallway, whereas in cases 2b and 3b the bedrooms are directly off the lounge (inner rooms). Here the risk in cases 2b and 3b is lower than the corresponding cases 2a and 3a; the larger volume available for smoke dispersal outweighs the greater ease for smoke to spread through the entire flat, and the increased provision of alarms will also be beneficial.

One option for a sensitivity study (further work) could be to look at the effect of increased alarms in cases 2a and 3a, ie in all rooms rather than just the hallway.

The cases with sprinklers (1c, 2c, 3c) all have significantly lower risk than cases without sprinklers. It has been assumed for these cases that sprinklers will always operate (provided the sprinkler head reaches its activation temperature) and will always suppress the fire once they have operated. While this is optimistic, it is likely not to be too unrealistic. Correctly maintained sprinkler systems have a very high reliability. Estimates vary, but the reliability will almost certainly be better than 90%. Sprinklers should at least prevent a fire from growing larger even if they do not succeed in extinguishing it once they have activated.

These results clearly indicate that open plan flats with sprinkler systems can achieve a significantly better level of safety, compared with AD B compliant designs.

Whether or not the increased coverage by smoke alarms provides a level of safety equivalent to or better than the AD B case is less clear-cut. Monte Carlo simulations, by their very nature, are subject to statistical uncertainties. These uncertainties are shown in Table 20, as 'error on mean' values. Consider, for example, cases 2a and 2b, where the mean ± error values for the number of deaths per fire

(Number_FED100) are 0.067 ± 0.009 and 0.044 ± 0.006 respectively. The difference between these two values is 0.023 ± $(0.009^2 + 0.006^2)^{½}$, which is significant at the 96.4% level (two-tailed test), ie there is only a 3.6% chance of a difference of this magnitude arising as a consequence of the statistical fluctuations in the two values being compared. For cases 3a and 3b, the difference is significant at the 89% level, and for cases 1a and 1b the differences are significant at the 97.2% level. In cases 2b and 3b the alarms are beneficial, but in case 1b they are insufficient to outweigh the effects of the changed geometry with respect to the AD B compliant design.

However, statistical fluctuations are not the only sources of uncertainty. The simulation model is not a perfect representation of reality; there may be some bias unknowingly introduced into the simulation results. While it is to be hoped that some of the bias may 'cancel out' when two or more cases are compared with one another, this cannot be guaranteed. The confidence that can be had for alarms alone making a significant difference is therefore reduced from the values calculated above. For this reason, a recommendation that additional alarms could provide equivalent safety would not be sufficiently robust.

6.8 Sensitivity of main results to selected assumptions

One possible source of bias in the case of alarms could be the times that have been assumed for the delays in people reacting and waking up. A sensitivity study was therefore performed to see if the results depend strongly on these assumptions.

Approximately 10 000 additional runs were performed for each of the nine cases, allowing the wake-up time to vary randomly as U(0,600), and the reaction time to vary randomly as U(0,60) for each run. Note that $U(x_1,x_2)$ is a random number uniformly distributed between x_1 and x_2.

Reaction time did not seem to make much difference. Results were more sensitive to the wake-up time. Figure 35 shows how the toxic dose per fire varies with the time required to wake up.

For the sensitivity analysis, the 'weighted average FED' was used as the risk metric. The weighted average FED is the average, per fire, of the sum of the dose received by all the people at risk from that fire. As shown in a previous paper,[10] this is a good measure for the overall risk since it is strongly correlated with the number of deaths but has a lower fractional error.

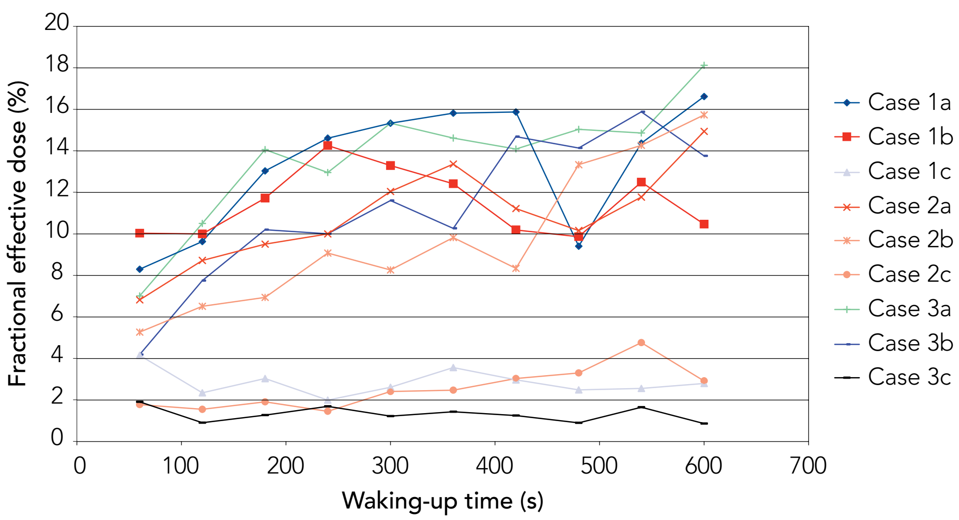


Figure 35 Sensitivity analysis results. Fractional effective dose per fire as a function of the time required to wake up.

The time for an awake person to react to an alarm did not seem to make much difference to the risk. The results were more sensitive to the time taken by sleepers to wake up. If Figure 35 is examined closely, it is possible to see that, for values of the waking-up time less than 300–400 s, the relative risk for cases 2b and 3b (inner rooms with enhanced detection and alarm coverage) is consistently lower than that for cases 2a and 3a (conventional flat designs with hallways).

For very large values of the waking-up time (greater than ~400 s), the results for cases 1a, 1b, 2a, 2b, 3a and 3b become more or less random, with no discernible trends, and large variability. The reasons for this randomness have yet to be explained and have not been pursued here. However, it does tend to reduce confidence in relying only on detection and alarms to achieve an equivalent level of safety to an AD B compliant design.

In cases 1a (bedsit) and 1b (inner room with enhanced detection and alarm coverage) the trend is less clear, with similar risks in both cases. It may be that the extra detection and alarm in case 1b is providing some compensation for the smaller room sizes, which would lead to faster smoke-filling times compared with case 1a. In the two- and three-bedroom flats, reduced risks are obtained for the cases with enhanced detection and alarm coverage and a larger living room compared to their conventional design counterparts.

It is not clear to what extent the results are affected by the assumed probabilities for various doors being left open. Survey data (see section 6.5.4) suggests it is quite likely that doors will be left open, and hence that smoke can affect the evacuation route regardless of whether the flat is open plan or a conventional layout.

Some more detailed analysis of the CRISP data has been undertaken in an attempt to determine precisely why the enhanced detector coverage of cases 2b and 3b leads to lower risks compared to cases 2a and 3a. This analysis has examined:

- the proportion of fires in which individual rooms became impassable owing to smoke-logging
- the distribution of times when individual rooms became impassable
- the amount of toxic dose absorbed within different rooms.

Unfortunately this analysis has proved inconclusive.

In order to better understand the complex interplay between the various dynamic factors, it is recommended that the risks for open plan designs with no additional fire protection features are also evaluated for comparison with the above results. Currently, it is not possible to say with a sufficiently high degree of confidence that enhanced detection alone will be at least as good as an AD B compliant design.

However, it is very clear that, regardless of the assumptions made about the time required to wake up following an alarm, sprinklers are beneficial (Fig. 35). (Cases 1c, 2c, 3c all have sprinklers).

6.9 Sprinkler activation

The effect of sprinkler downdrag will be to dilute the smoke. If it is assumed that the cold layer has negligible optical density, then mixing the hot and cold layers will produce an optical density of OD(hot) * (2.4 - clrdepth)/2.4 where 2.4 m is the ceiling height, and clrdepth was the height of the smoke layer above the floor just before sprinkler operation. If the smoke layer was above head height before operation then things will get worse since the mixed OD will be greater than OD(cold). Conversely, if the smoke layer was below head height then conditions will improve with the dilution of the smoke. However, there will be additional effects when sprinklers operate – condensing steam/water droplets will reduce visibility, and the fire may produce more visible smoke per kg fuel while being suppressed than while burning ‘freely’. CRISP does not model downdrag or other visibility effects of sprinkler operation. It was necessary, therefore, to investigate the layer height and OD when sprinklers activate, to estimate the likely consequences in terms of visibility.

The 'escape' action in CRISP assumes that people will be prepared to enter smoke that does not exceed the tenability limit for optical density (0.5 m^{-1}). However, if they are in a room and conditions worsen, the 'leave room' action will attempt to take them to the nearest location where conditions are less severe – they might manage to escape as a result of this, or they might end up 'trapped' in an inner room.

The CRISP model's output subroutines have been slightly modified, in order to indicate simulations where one or more people were 'trapped' (ie unable to reach an exit owing to the severity of the smoke), even if this only applied for a brief duration. The proportion of simulations where someone was trapped is shown in Figure 36.

The cases where there are sprinklers present, cases 1c, 2c and 3c, all have a lower proportion of fires where people are trapped, compared with the corresponding cases where there are no sprinklers. This is evidence that sprinklers do make it easier for people to escape, rather than only reducing risk by enabling people to survive for extended periods trapped within the building.

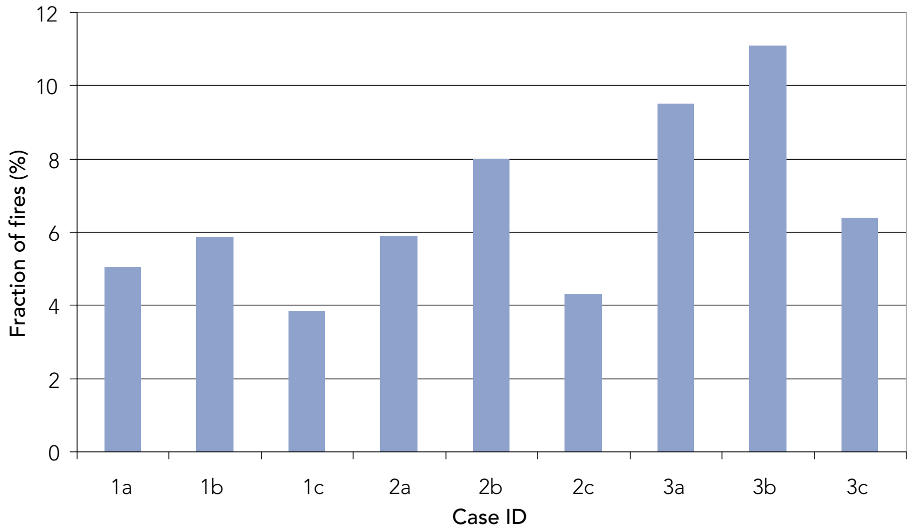


Figure 36 The fraction of fires where smoke prevents escape.

Note that the fraction of fires where smoke prevents escape is higher for enhanced detector and alarm coverage (cases 2b and 3b), compared with the corresponding conventional flat designs (cases 2a and 3a), although other results have previously shown that cases 2b and 3b have lower risk. This is a further reason why enhanced detector and alarm coverage without also including sprinklers is not recommended as a means of ensuring that open plan flats have risks that are the same as or lower than equivalent AD B compliant designs.

A very crude model of sprinkler downdrag was incorporated into the CRISP simulation. For this model, it was assumed that whenever a sprinkler operated, the room would become impassable owing to downdrag. People would leave if already within the room, but would not enter if they were outside it. Re-running the sprinklered cases with this model produced outcomes identical to those for the version of the model without downdrag. Therefore it is clear that in the room of fire origin, by the time a sprinkler operated conditions were so bad that people would not enter that room anyway, whether or not downdrag occurred.

However, sprinklers can reduce the chance of people being trapped by smoke in other rooms besides that of the fire origin. Consider an example where there is a fire is in a bedroom, and people in other bedrooms (all bedrooms adjoining the living room).

People need to pass through the living room in order to escape. When the sprinkler in the room of fire origin operates and the fire is extinguished or controlled, there will be less smoke entering the living room; therefore people in other rooms will be more likely to be able to pass through.

These results enhance the robustness of the conclusion that sprinklers significantly reduce the risk in open plan flats.

Finally, the conditions prevailing at the point of sprinkler activation have been investigated. Since the fire itself has considerable variability (eg item type, room of origin), there is variability in the conditions at activation. The results (see the CD-Rom) obviously cannot be compared directly with any experimental results, but nevertheless are in good qualitative agreement with results obtained from, for example, the series of experiments investigating the effectiveness of residential sprinklers.[7]

6.10 Conclusions and recommendations

It has been demonstrated that CRISP or an equivalent tool that considers all aspects of the whole system, including human behaviour, can be utilised to compare risks in open plan and conventional AD B compliant flats.

The detailed conclusions that apply to the specific layouts and the simulations carried out are:

- Flat size/travel distance does not seem to be a significant factor.
- The open plan designs with enhanced detection have risks of death and injury similar to those for AD B compliant flats. At present it is not possible to reach a robust conclusion that enhanced detection can offer equivalent or better levels of safety compared with AD B compliant flats.
- The open plan flats with a sprinkler system (in accordance with BS 9251[4] or BS EN 12845,[13] as appropriate) and an enhanced detection system (LD1 system in accordance with BS 5839-6[3]) can provide a level of safety that is at least as good as that of a similar AD B compliant design.

Sensitivity analyses were carried out on the reaction and waking times in order to improve the robustness of the conclusions.

Further analysis has also been carried out to investigate whether the reduction of risk in the sprinklered cases was due to people surviving for extended periods, trapped within the building. It was found that this was not happening. In fact, people were trapped in a smaller proportion of fires when sprinklers were present. This result also improves the robustness of the conclusion that sprinklers significantly reduce the risk.

More work is needed if conclusions about comparisons of risks of death and injury can be drawn for generic cases rather than the specific cases generated.

Whether sprinklers would be a cost-effective option has not been addressed by this study. The greater value of an open plan flat compared with one of the same floor area that includes a hallway could compensate (or exceed) the cost of installing a sprinkler system.

APPENDIX C

Computer modelling, supplementary results

All the graphs relating to the text in appendix C are included as PDFs on the accompanying CD-Rom. The graphs, pertaining to a particular case, are collated in their own PDF file labelled as case studies as follows:

- Case1a.pdf
- Case1b.pdf
- Case1c.pdf
- Case2a.pdf
- Case2b.pdf
- Case2c.pdf
- Case3a.pdf
- Case3b.pdf
- Case3c.pdf.

In order to compare results from different cases for a particular parameter, the files can be opened in separate windows, or printed out. To aid such comparisons, all graphs for a given parameter will have the same scales for the axes. In some cases this means that results greater than the largest axis value cannot be plotted. However, the trends are clear.

The CD-Rom also includes the results of the sensitivity analysis and the visibility study as PDFs:

- Sensitivity analysis.pdf
- Visibility study.pdf.

Nine cases have been modelled, in three groups of three. The three groups represent a one-bedroom flat/bedsit, a medium-sized two-bedroom flat, and a large three-bedroom flat. Within each group there are three options, based on a similar floor plan, representing an AD B compliant case, an alternative case, and the alternative case plus sprinkler protection.

The nine cases are summarised in Table 21. (Full details, including floor plans, are in appendix B.)

Table 21

Summary of the CRISP modelling cases

Case	Bedrooms	Configuration	Footprint*	Alarms	Sprinklers
1a	One (studio/bedsit)	AD B compliant	8 m × 4 m	LD3‡	No
1b	One	Open plan/inner room†	8 m × 4 m	LD1§	No
1c	One	Open plan/inner room†	8 m × 4 m	LD1§	Yes
2a	Two	AD B compliant	10 m × 8 m	LD3‡	No
2b	Two	Open plan/inner room	10 m × 8 m	LD1§	No
2c	Two	Open plan/inner room	10 m × 8 m	LD1§	Yes
3a	Three	AD B compliant	16 m × 12 m	LD3‡	No
3b	Three	Open plan/inner room	16 m × 12 m	LD1§	No
3c	Three	Open plan/inner room	16 m × 12 m	LD1§	Yes

* Ceiling height is 2.4 m in all cases.
† 9 m travel distance measured to back of inner room case.
‡ LD3 system, smoke alarm in the circulation space.
§ LD1 system, smoke alarm in each room.

6.11 Results for each case

The results for each case, illustrated as graphs, are contained on the accompanying CD-Rom (eg case 1a.pdf, case 1b.pdf). Each of the graphs uses the same headings shown in this section (section 6.11).

Basic risk calculations

The mean (average) number of various quantities, also the standard deviation and the error on the mean. This last value is calculated by dividing the standard deviation by the square root of the number of simulations performed for this case (typically between 1000–1500).

The quantities listed in this calculation are:

- number at risk – the number of people inside at the start of the simulation
- number of dependents – the number of people inside at the start who rely on others to tell/assist them to leave
- number immobile – the number of dependents inside at the start who cannot move by themselves
- number inside – the number of people inside at the end of each simulation (excluding those who are 'dead')
- number with FED>1% – the number of people at the end of each simulation who have acquired a fractional effective dose of 1% or more (this might be roughly equivalent to those sent to hospital for a precautionary check following a real fire)
- number with FED>3% – the number of people at the end of each simulation who have acquired a fractional effective dose of 3% or more (note that this is a subset of those with a dose of 1% or more)
- number with FED>10% – the number of people at the end of each simulation who have acquired a fractional effective dose of 10% or more (this might be roughly equivalent to those recorded as a 'smoke inhalation' injury following a real fire)

- number with FED>30% – the number of people at the end of each simulation who have acquired a fractional effective dose of 30% or more
- number with FED=100% – the number of people at the end of each simulation who have acquired a fractional effective dose of 100% (these people are considered to be 'dead')
- weighted average FED – this is the total dose acquired by all the people initially present at the start of the simulation. It is a convenient single metric to represent the life safety risk. Note, however, that a value of 50 (for example) could arise as a result of one occupant receiving a dose of 10%, plus two others with a dose of 20% each; alternatively it could arise from a single occupant receiving a dose of 50%.

Frequency distribution of time of fire ignition

Fraction of all fires (%), categorised by the time when the fire starts (24-hour clock). This is a direct reflection of the input probability distribution.

Frequency distribution of type of burning item

Fraction of all fires (%), categorised by the type of burning item. This is a direct reflection of the input probability distribution. Note that not all item types are available in the list of contents for each building.

Frequency distribution of peak heat release rate

Fraction of all fires (%), categorised by the peak heat release rate achieved by the fire.

Frequency distribution of peak temperature rise

Fraction of all fires (%), categorised by the maximum temperature of the hot smoke layer attained during the fire.

Frequency distribution of fire origin

Fraction of all fires (%), categorised by the type of the room where the fire occurs. This is a direct reflection of the input probability distribution.

Frequency distribution of time for temperature to rise by 550K

Fraction of all fires (%), categorised by the time after ignition when the temperature rise (above normal ambient) of the hot smoke layer first exceeds 550K. At this point the amount of thermal radiation from the hot smoke layer is likely to trigger flashover.

A value of 'N/A' indicates that the necessary threshold was not exceeded for a particular fire.

Frequency distribution of time to first window cracking

Fraction of all fires (%), categorised by the time after ignition when the first window cracks. This will be when the smoke layer temperature to which the glass is exposed is 90°C.

A value of 'N/A' indicates that no window cracked in a particular fire.

Frequency distribution of time to first window breaking

Fraction of all fires (%), categorised by the time after ignition when the first window breaks. This will be when the smoke layer temperature to which the glass is exposed is between 250°C–350°C. Some fraction of the glass will fall out. This then provides a route for fresh air to feed the fire.

A value of 'N/A' indicates that no window broke in a particular fire.

Frequency distribution of time for window to fall out

Fraction of all fires (%), categorised by the time after ignition when the first window falls out completely. This will be when the smoke layer temperature to which the glass is exposed is between 400°C–600°C. This then provides a route for more fresh air to feed the fire.

A value of 'N/A' indicates that no window completely fell out in a particular fire.

Frequency distribution of time to automatic fire detection

Fraction of all fires (%), categorised by the time after ignition when the first smoke alarm operates.

A value of 'N/A' indicates that a smoke alarm did not operate in a particular fire.

Frequency distribution of time to sprinkler operation

Fraction of all fires (%), categorised by the time after ignition when the first sprinkler operates. Note this is only plotted for cases 1c, 2c and 3c.

A value of 'N/A' indicates that a sprinkler did not operate in a particular fire (usually because the smoke layer temperature was not hot enough).

Frequency distribution of time for last person to exit

Fraction of all fires (%), categorised by the time after ignition when the last person leaves the flat.

A value of 'N/A' indicates that somebody was still in the flat (alive or dead) at the end of the simulation for a particular fire.

A comparison between this graph and the frequency distribution of the time for the first person to die can give a crude assessment for the risk of death (the actual risk graphs later are more precise).

Frequency distribution of time for first person to die

Fraction of all fires (%), categorised by the time after ignition when the first person dies.

A value of 'N/A' indicates that nobody died in a particular fire.

Frequency distribution of number of people at risk

Fraction of all fires (%), categorised by the number of people in the flat when the fire starts. This is a reflection of the number of people in the family, the time of day when a particular fire starts, and the probability of each person being at home at that time.

Frequency distribution of number of dependent people

Fraction of all fires (%), categorised by the number of dependent people in the flat when the fire starts. This is a reflection of the number of dependent people in the family, the time of day when a particular fire starts, and the probability of each dependent person being at home at that time.

Frequency distribution of number of immobile people

Fraction of all fires (%), categorised by the number of immobile people in the flat when the fire starts. This is a reflection of the number of immobile people in the family, the time of day when a particular fire starts, and the probability of each immobile person being at home at that time.

Frequency distribution of number of people still inside at end of fire

Fraction of all fires (%), categorised by the number of people still inside the flat (but not dead) for a particular fire.

Frequency distribution of number of people with FED > 1%

Fraction of all fires (%), categorised by the number of people who have at least a small (1%) fractional effective toxic dose (FED). A dose of this level might correspond to a 'precautionary check' in the UK Fire Statistics for fire injuries. When a person's FED reaches 100% they are assumed to be dead.

Frequency distribution of number of people with FED > 3%

Fraction of all fires (%), categorised by the number of people who have at least a small (3%) fractional effective toxic dose (FED). A dose of this level might correspond to a 'precautionary check' in the UK Fire Statistics for fire injuries. When a person's FED reaches 100% they are assumed to be dead.

Frequency distribution of number of people with FED > 10%

Fraction of all fires (%), categorised by the number of people who have at least a significant (10%) fractional effective toxic dose (FED). A dose of this level might correspond to a significant injury in the UK Fire Statistics for fire injuries. When a person's FED reaches 100% they are assumed to be dead.

Frequency distribution of number of people with FED > 30%

Fraction of all fires (%), categorised by the number of people who have at least a serious (30%) fractional effective toxic dose (FED). A dose of this level might correspond to a serious injury in the UK Fire Statistics for fire injuries. When a person's FED reaches 100% they are assumed to be dead.

Frequency distribution of number of people with FED = 100%

Fraction of all fires (%), categorised by the number of people who have a fatal (100%) fractional effective toxic dose (FED). A dose of this level would correspond to a fatality in the UK Fire Statistics.

Frequency distribution of total toxic dose per fire

Fraction of all fires (%), categorised by the total toxic dose received by all the occupants for a particular fire. Note that it is possible for this total dose to exceed 100%, if there is more than one person present. For example, if there were two people present, one with a dose of 60%, and one with a dose of 45%, then the total dose for that fire would be 105%.

The total toxic dose per fire provides a good risk metric (it is more sensitive than simply working out the risk of death, ie the number of people per fire with FED = 100%).

Death modes

The average number of fatalities per fire, categorised in various ways. The first has three sub-categories, which are:

- Dead_in_fire – the person died in the room of fire origin.
- Dead_adjacent – the person died in a room adjacent to the room of fire origin.
- Dead_far – the person died somewhere else.

The second way has two sub-categories:

- Dead_stuck – the person was prevented from leaving because of smoke blocking the route, and died later.
- Dead_overtaken – the person did not have sufficient time to exit the building before they died. (This usually means the person was alerted late, or was slow-moving or immobile.)

Risk of death versus time of fire ignition

Average number of deaths per fire, categorised by the time when the fire starts (24-hour clock).

Risk of death versus type of burning item

Average number of deaths per fire, categorised by the type of burning item. Generally speaking, the faster the fire grows and the bigger it gets, the greater the risk.

Risk of death versus peak heat release rate

Average number of deaths per fire, categorised by the peak heat release rate achieved during the fire.

Risk of death versus peak temperature rise

Average number of deaths per fire, categorised by the maximum temperature of the hot smoke layer attained during the fire.

Risk of death versus fire origin

Average number of deaths per fire, categorised by the type of the room where the fire occurs.

Risk of death versus time for temperature to rise by 550K

Average number of deaths per fire, categorised by the time after ignition when the temperature rise (above normal ambient) of the hot smoke layer first exceeds 550K. At this point the amount of thermal radiation from the hot smoke layer is likely to trigger flashover.

A value of 'N/A' indicates that the necessary threshold was not exceeded for a particular fire.

Risk of death versus time to automatic fire detection

Average number of deaths per fire, categorised by the time after ignition when the first smoke alarm operates.

A value of 'N/A' indicates that a smoke alarm did not operate in a particular fire.

Risk of death versus number of people at risk

Average number of deaths per fire, categorised by the number of people in the flat when the fire starts.

Risk of death versus number of dependent people

Average number of deaths per fire, categorised by the number of dependent people in the flat when the fire starts.

The risk is positively correlated with the number of dependents, since they rely on others to assist them (although they can leave untenable rooms unaided).

Risk of death versus number of immobile people

Average number of deaths per fire, categorised by the number of immobile people in the flat when the fire starts.

The risk is positively correlated with the number of immobile dependents, since they rely on others to assist them.

Relative risk versus time of fire ignition

Average of the total toxic dose for all the occupants per fire, categorised by the time when the fire starts (24-hour clock).

Relative risk versus type of burning item

Average of the total toxic dose for all the occupants per fire, categorised by the type of burning item. Generally speaking, the faster the fire grows and the bigger it gets, the greater the risk.

Relative risk versus peak heat release rate

Average of the total toxic dose for all the occupants per fire, categorised by the peak heat release rate achieved during the fire.

Relative risk versus peak temperature rise

Average of the total toxic dose for all the occupants per fire, categorised by the maximum temperature of the hot smoke layer attained during the fire.

Relative risk versus fire origin

Average of the total toxic dose for all the occupants per fire, categorised by the type of the room where the fire occurs.

Relative risk versus time for temperature to rise by 550K

Average of the total toxic dose for all the occupants per fire, categorised by the time after ignition when the temperature rise (above normal ambient) of the hot smoke layer first exceeds 550K. At this point the amount of thermal radiation from the hot smoke layer is likely to trigger flashover.

A value of 'N/A' indicates that the necessary threshold was not exceeded for a particular fire.

Relative risk versus time to automatic fire detection

Average of the total toxic dose for all the occupants per fire, categorised by the time after ignition when the first smoke alarm operates.

A value of 'N/A' indicates that a smoke alarm did not operate in a particular fire.

Relative risk versus number of people at risk

Average of the total toxic dose for all the occupants per fire, categorised by the number of people in the flat when the fire starts.

Relative risk versus number of dependent people

Average of the total toxic dose for all the occupants per fire, categorised by the number of dependent people in the flat when the fire starts.

The risk is positively correlated with the number of dependents, since they rely on others to assist them (although they can leave untenable rooms unaided).

Relative risk versus number of immobile people

Average of the total toxic dose for all the occupants per fire, categorised by the number of immobile people in the flat when the fire starts.

The risk is positively correlated with the number of immobile dependents, since they rely on others to assist them.

6.12 Sensitivity analysis

A sensitivity study was performed to see if the results depend strongly on the times that we have assumed for the delays in people reacting and waking up.

Reaction time did not seem to make much of a difference. Results were more sensitive to the wake-up time. The file Sensitivity analysis.pdf shows how the average of the total toxic dose for all occupants per fire varies with the time required to wake up. If the graph is examined closely, it is possible to see that, for values of the waking up time less than 300–400 s, the relative risk for cases 2b and 3b (inner rooms with enhanced detection and alarm coverage) is consistently lower than that for cases 2a and 3b (conventional flat designs with hallways). For very large values of the waking-up time (greater than ~400 s), the results for cases 1a, 1b, 2a, 2b, 3a and 3b become more or less random, with no discernible trends, and large variability. The reasons for this behaviour have yet to be explained and have not been pursued here.

In cases 1a (bedsit) and 1b (inner room with enhanced detection and alarm coverage) the trend is less clear, with similar risks in both cases. It may be that the extra detection and alarm in case 1b is providing some compensation for the smaller room sizes which would lead to faster smoke-filling times, compared with case 1a. In the two- and three-bedroom flats, reduced risks are obtained for the cases with enhanced detection and alarm coverage and a larger living room than the conventional design counterparts.

However, it is very clear that, regardless of the assumptions made about the time required to wake up following an alarm, sprinklers are beneficial. (Cases 1c, 2c, 3c all have sprinklers.)

6.13 Visibility study

This study investigated the proportion of all fires where people were prevented (however briefly) from escaping as a consequence of severe smoke conditions, eg high optical density, smoke/air interface down to head height.

This study also recorded the smoke conditions (temperature, optical density and smoke/air interface height) at the time when sprinklers activate, to estimate the likely consequences in terms of visibility. Since the fire itself has considerable variability (eg item type, room of origin), there is variability in the conditions at activation. The results obviously cannot be compared directly with any experimental results, but nevertheless are in good qualitative agreement with results obtained from, for example, the series of experiments investigating the effectiveness of residential sprinklers.

Cases 1a–3c: Frequency distribution of number of fires where smoke prevents escape

Fraction of all fires (%), categorised by the simulation case ID (1a–3c), where one or more people were 'trapped' (ie unable to reach an exit owing to the severity of the smoke), even if this only applied for a brief duration.

The cases where there are sprinklers present, cases 1c, 2c and 3c, all have a lower proportion of fires where people are trapped, compared to the corresponding cases where there are no sprinklers. This is evidence that sprinklers do make it easier for people to escape, rather than only reducing the risk by enabling people to survive for extended periods trapped within the building.

Re-running the sprinklered cases with a crude model of downdrag (ie a room becomes impassable once sprinklers have operated) produced outcomes *identical* to those for the version of the model without downdrag. Therefore it is clear that by the time a sprinkler operated, conditions were so bad in the space where the sprinkler had operated that people would not enter the space anyway.

Case 1c: Frequency distribution of smoke temperature rise at sprinkler activation

Fraction of all fires (%), categorised by the smoke temperature rise at sprinkler activation, for case 1c.

Case 2c: Frequency distribution of smoke temperature rise at sprinkler activation

Fraction of all fires (%), categorised by the smoke temperature rise at sprinkler activation, for case 2c.

Case 3c: Frequency distribution of smoke temperature rise at sprinkler activation

Fraction of all fires (%), categorised by the smoke temperature rise at sprinkler activation, for case 3c.

Case 1c: Frequency distribution of smoke optical density at sprinkler activation

Fraction of all fires (%), categorised by the smoke optical density at sprinkler activation, for case 1c.

Case 2c: Frequency distribution of smoke optical density at sprinkler activation

Fraction of all fires (%), categorised by the smoke optical density at sprinkler activation, for case 2c.

Case 3c: Frequency distribution of smoke optical density at sprinkler activation

Fraction of all fires (%), categorised by the smoke optical density at sprinkler activation, for case 3c.

Case 1c: Frequency distribution of clear depth under smoke layer at sprinkler activation

Fraction of all fires (%), categorised by the clear depth under the smoke layer at sprinkler activation, for case 1c.

Case 2c: Frequency distribution of clear depth under smoke layer at sprinkler activation

Fraction of all fires (%), categorised by the clear depth under the smoke layer at sprinkler activation, for case 2c.

Case 3c: Frequency distribution of clear depth under smoke layer at sprinkler activation

Fraction of all fires (%), categorised by the clear depth under the smoke layer at sprinkler activation, for case 3c.

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Open plan flat layouts

Assessing life safety in the event of fire

There has been an increase recently in open plan flat layouts in the UK with bedrooms located as inner rooms. While these designs may appeal to the market, such layouts can pose problems for designers and developers particularly where they may not accord easily with Building Regulations and guidance.

This research report is the result of a study examining the options for satisfying the requirements of the Building Regulations. It addresses layout, size, travel distances, enhanced detection options and sprinkler use. In addition it addresses the human implications, including the various reactions, wake up and response times from people occupying the building.

Scenario modelling has been undertaken – using a unique evacuation and fire spread computer programme – to compare the risk to life of different layouts and situations. Full results of all the scenarios can be found on the accompanying CD-Rom.

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The NHBC Foundation has been established by NHBC in partnership with the BRE Trust. It facilitates research and development, technology and knowledge sharing, and the capture of industry best practice. The NHBC Foundation promotes best practice to help builders, developers and the industry as it responds to the country's wider housing needs. The NHBC Foundation carries out practical, high quality research where it is needed most, particularly in areas such as building standards and processes. It also supports house builders in developing strong relationships with their customers.

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