Fire Engineering Practitioner Tools: Survey and Analysis of Needs

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About the SFPE Foundation:

The Society of Fire Protection Engineers (SFPE) established the SFPE Educational and Scientific Foundation in 1979. The Foundation is a charitable 501(c)(3) organization incorporated in the state of Massachusetts in the United States of America. It supports a variety of research and educational programs in service of its mission to enhance the scientific understanding of fire and its interaction with the natural and built environment.

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Table of Contents

List of Tables

List of Figures

1. Executive Summary

This project was carried out for the Society of Fire Protection Engineers (SFPE) Research Foundation. The objectives of the project, in relation to fire engineering tools, were to understand the common tasks and workflow of practising fire engineers, identify the tools needed by them and the current gaps between the common practices and available practical tools. Given this knowledge, future work to fill these gaps and develop new tools can be proposed.

1.1 The survey

An online survey was developed because it enabled a larger reach to an international audience increasing the potential audience. The main target was SFPE members and others conducting similar work. The survey was designed using the web-based GDPR compliant Qualtrics Survey Platform at the University of Canterbury. Data collection was anonymous using the options available in the Qualtrics system. An ethics application (HEC 2020/73/LR-PS) was made and approved by the University of Canterbury.

Data was collected over the period from February 9 to June 7, 2021. A total of 156 practitioners from 32 countries agreed to complete the survey. A total of 70% were SFPE members, with 63% working in the design sector and 9% working in the research, education or testing sectors. The survey respondents were generally experienced practitioners with 54% having at least 15 years work experience in a fire-related field. They were also well qualified with 62% holding a Masters degree.

Most respondents were employed in the USA (33%) followed by New Zealand (12%), Canada (8%), Australia (6%) and United Kingdom (6%). When compared with the SFPE membership data the proportion of respondents from the USA under-represented the membership by a factor or about two, whereas the responses from New Zealand participants were over-represented by a factor of about 6. Participants from Canada, Australia, Sweden and the United Kingdom were also over-represented to varying degrees. Notwithstanding these differences from the SFPE membership as a whole, and while there may be differences in the selection and ranking of individual calculation tools in different countries, we consider that the overall findings and recommendations made in this study remain valid.

There was potential for some survey bias, based on the individuals who chose to respond not being truly representative of SFPE interests. For example there was almost no mention of fire practitioner needs in the wildland fire area and also relatively little generally mentioned that related to sustainability. This should be kept in mind when considering the survey results.

Fire engineering tools were most frequently used for calculations of fire and/or smoke development (including radiation and smoke management) at 66% while 56% of respondents had used tools for egress calculations. These were followed by information management tools (e.g. BIM/CAD) (42%), hydraulic flows, detection and suppression design (40%), response to elevated temperatures (35%) and for risk analysis (33%).

The top ten most common software tools mentioned, excluding various spreadsheet and in-house tools, were Fire Dynamics Simulator (FDS), Pathfinder, Pyrosim, AutoCAD, CFAST, Revit, B-RISK, Smokeview, HASS and FireWind.

The most common computing platform used on a weekly basis was a local personal computer (64%) followed by inhouse computer clusters (31%), websites (10%), tablets or phones (11%) and third-party computing clusters the least commonly used on a weekly basis (6%). When asked about the preferred computing platforms for the future, the most common reply was still a local personal computer, followed by cloud services and with tablets or phones being the least popular.

The most common specific tool requested by an Authority Having Jurisdiction (AHJ) was CFD analysis using FDS. There were some AHJ's that request CONTAM anaysis be provided for zoned smoke control or stair pressurisation design. In Portugal, the ARICA model is specifically mentioned as being required for existing buildings.

1.2 Recommendations for future work plan

The survey respondents were asked to identify the gaps in existing tools and where new tools are needed. The research team have made a series of recommendations informed by the data gathered from the survey responses during the course of the present project (i.e. primarily the gaps and future needs identified from the survey). The SFPE Research Roadmap is also referred to as a basis for prioritising the different elements of the future work plan recommendations.

Our recommendations are grouped into the general themes of data; guidance; integration; new tools; physics and conceptual submodels; regulation; user experience; and validation. Our recommendations, informed by the survey responses, are: [1]

Data

1. Develop an RfP that specifically focuses on identifying and prioritizing data needs for fire engineering purposes and how those priority needs might be addressed

2. Identify opportunities to update (existing), develop (new), populate, host, maintain and fund fire engineering databases – it is assumed that such opportunities would be beyond the means of the Foundation/Society and would therefore follow a 'shared model' approach with industry, academia, etc.

3. Develop formal SFPE guidance on data and databases for fire engineering.

Guidance

4. Develop an awareness campaign that promotes the importance and requirements of fire model usage guidance.

5. Review existing (SFPE and external) guidance on different types of fire model usage and recommend opportunities to revise and improve existing guidance.

6. Develop and deliver education/training on fire model usage guidance.

Integration

7. Develop and RfP to investigate the feasibility and opportunities for increased and improved tool and model integration including:

[1] The sequential numbering is not intended to indicate priority.

- BIM/CAD Add-ins generally
- Fire-evacuation models
- Fire-FEA models
- Fire-hydraulic models
- Linkages to QRA models.

8. Develop a publicity campaign that highlights opportunities to utilise BIM more frequently and effectively in fire engineering applications.

New tools

9. Establish a Working Group to undertake work to identify and prioritize needs for hand-calculation/spreadsheet methods.
10. Engage with international academic institutes to include priority topics as post-graduate student projects to develop spreadsheet tools.
11. Develop an RfP that specifically focusses on existing QRA models and usage in fire risk assessment applications and which links to the content of the SFPE Risk Guide.

Physics and conceptual submodels

12. Establish an SFPE Working Group to investigate the state-of-the-art with regard to submodel usage in broader fire models and to identify and prioritize opportunities to both improve/enhance existing submodels and to develop new submodels where gaps exist.
13. Based on this prioritisation, develop an RfP as required to address both existing and new submodels.

Regulation

14. Engage with fire engineering sector to investigate need and/or feasibility for 'code-checking tools'.
15. Based on outcome of this investigation, develop and RfP that systematically investigates the feasibility of developing and implementing 'code-checking' tools and identifies similar initiatives that may be occurring internationally.
16. If appropriate, develop a pilot 'code-checking' tool and a case study to demonstrate feasibility and application in a real-world environment.

User experience

17. Establish a Work Group to identify and investigate opportunities to improve the user interface experience of model users.
18. Develop a document that describes the standard features required for a model user interface.

19. Develop an RfP to investigate existing examples and opportunities to improve model input/output visualisation, etc.

Validation

20. Encourage developers of FSE models to adopt continuous integration processes as part of model development and encourage model users to make use of validation and benchmarking cases to support the applications for which they are using models for.

Other

Additional recommendations, not linked to the survey responses, are:

21. Repeat a fire model usage survey on a regular basis (every three years).
22. Develop an SFPE Engineering Guide which covers all aspects of best-practice fire engineering tool usage, and that includes a current listing of current models, updated on the same cycle as the regular survey. The new Guide should also be developed to complement the existing SFPE "Substantiating a Fire Model" Guide.

    - Approach SFPE Subcommittee for Standards Oversight with recommendations for new work items.

    - Establish Task Group to oversee development of new Guide
23. Conduct regular SFPE education/training for fire engineers on best-practice fire model usage.
24. Regularly promote and publicise best-practice fire model usage to the SFPE membership.
25. Engage with SFPE Subcommittee for Research and Innovation to ensure that fire model usage has suitable prominence and representation in future versions of the SFPE Research Roadmap.

1.3 Prioritization of recommendations

As well as making 25 recommendations in subsections 8.1 to 8.9, in this subsection the authors also identify what they consider to be the top three priority themes (rather than individual recommendations) for future Society/Foundation research and research funding initiatives.

1. Priority Theme 1 – Data
   As noted in subsection 8.1 of this report, the survey identified that there is a lack of quality data (and associated databases) for calculation and modelling purposes. Coupled with data also being a priority topic in the SFPE Research Roadmap, the authors consider that the topic of data should be the highest priority for future Society/Foundation research and research funding initiatives. Furthermore, rather than focus on any one single recommendation for future workplans in isolation, the authors consider that a comprehensive approach should be taken to this topic, and that

such efforts be undertaken in a broad, collaborative manner with the key stakeholders and organisations in the sector.

2. Priority Theme 2 – Integration
   As noted in subsection 8.3, the authors provide two recommendations for future workplans relating to 'integration'. Based on survey feedback, of particular concern to the authors were responses indicating that fire engineers are falling behind other design sectors with regard to BIM uptake and usage. In the authors' opinion, this is also consistent with the priority given to BIM in the SFPE Research Roadmap. On this basis, the authors consider that integration should be the second highest for the future Society/Foundation research and research funding initiatives, and that amongst the various integration opportunities identified in subsection 8.3, priority should be given to BIM integration.

3. Priority Theme 3 – New Tools
   As noted in subsection 8.4, the authors make a series of recommendations in relation to 'new tools'. Based on the breadth of feedback from the survey on this topic, and the central role that engineering tools play in the life of fire engineering practitioners, the authors consider that 'new tools' should be the third highest priority for the future Society/Foundation research and research funding initiatives. The authors also believe that QRA tools used in fire risk assessment should be given prominence.

2. Introduction

2.1 Background

There has been significant effort to enhance our understanding of fire safety in the built environment, including both fire dynamics and evacuation systems over the past 60 years and this has led to the development of numerous models and tools over that period intended to be useful to support performance-based design, fire forensics, fire forecasting, and other applications. Many of these tools are now outdated or no longer supported or maintained and may not be aligned with the current best practices of the profession (or may not even be usable or compatible with modern computer operating systems). There are also likely to be new areas of research in which practical tools have still yet to be developed.

Previous surveys of fire models have been conducted. In 1992 an international survey of fire models for fire and smoke by Raymond Friedman was published in the SFPE Journal of Fire Protection Engineering [1]. This survey listed 62 models divided into various categories (e.g. zone models, field models, evacuation models etc.). Very few of these models are in current use today. The survey was updated in 2003 by Olenick and Carpenter [2] and again published in the SFPE Journal of Fire Protection Engineering. Further updates were conducted in 2007, 2010, and 2013/2014 by Combustion Science and Engineering with the most recent results included on a website (http://firemodelsurvey.com/index.html). Models were identified as either actively supported or archived. Since then there have been other tools developed such as the Nuclear Regulatory Commission Fire Dynamics Toolset (NRC FDT) created in 2013. The FDTs were developed using state-of-the-art fire dynamics equations and correlations that were preprogrammed and locked into Microsoft Excel® spreadsheets [3]. While much of the early model development focused on fire development, increasing attention has been given to evacuation modeling with one of the earliest reviews by Gwynne et al. [4] in 1999 identifying 22 models. In 2005, Kuligowski and Peacock [5] reported on 26 evacuation models and this was updated in 2010 [6]. This latter review covered a total of 30 computer models that focus on providing evacuation data from buildings. Mostly recently, a survey of pedestrian evacuation model usage by Lovreglio et al. [7] mentioned 72 models. Finally, while fire and evacuation modeling has been mostly reliant on desktop computers, there is now more use of cloud computing [8] as well as mobile phone platforms (e.g. Thiriet [9]). It is also possible that the needs of the fire engineers may have changed over time and it is not clear how many different models are actually in common use, and to what extent the available models and tools meet the current and future needs of the profession. There is a need to gather data to understand typical fire engineering calculations done and to identify where effort is needed to fill gaps and develop new tools that will support fire engineers in the future.

2.2 Objectives

The specific objectives of the present study (in relation to fire engineering tools) are to:

1. understand the common tasks and workflow of practicing fire engineers
2. identify the tools needed to support engineers in the practice of fire engineering
3. identify gaps between the common practices and available practical tools.

3. Methodology

The methodology used in the project is described in the following three tasks.

Task 1:

Conduct an international survey of fire engineers and practitioners from the government, private and public sectors to identify the common tasks and practices employed by them. The intent of the survey is to determine the common calculations performed, how often they are done, how complicated they are perceived to be, and what applications they are for. The survey would complement the previous compilations of models undertaken by Olenick and Carpenter [2] and Lovreglio et al. [7] but also provide information on the types of common calculations being done and what the current gaps are and future needs of the fire engineering community.

Task 2:

Based on the results of the survey carried out in Task 1, and other resources (e.g. other reviews and compilations) identify:

1. The tools necessary to support the profession
2. A list of current tools and their level of complexity vs detail/output/practicality with emphasis on the tools mentioned in the survey. Identify whether the tool is up to date, maintained, and readily usable.
3. Document the fundamental features of these models and their user interfaces.

Task 3:

Based on Task 1 and 2 identify what current maintained existing set of tools match up with common practice and where the gaps exist to aid in generating a Gaps Analysis and Needs List. Finally, a plan is developed for work needed to develop or support a suite of tools to meet the needs of today's and future fire engineering practitioners.

4. Survey of Fire Engineering Tools

4.1 Survey method and description

An online survey was developed which included a set of both open- and closed-ended questions. An online survey was chosen because it enabled a larger reach to an international audience increasing the potential audience.

The survey was designed using the web-based GDPR compliant Qualtrics Survey Platform at the University of Canterbury. Data collection was anonymous using the options available in the Qualtrics system. An ethics application (HEC 2020/73/LR-PS) was made and approved by the University of Canterbury.

The survey was targeted at practising fire engineers and promoted via SFPE channels primarily being through LinkedIn and email. The following information about the survey was provided to potential respondents.

> **About the survey** As part of a project funded by the SFPE Educational & Scientific Foundation, researchers from Fire Research Group (FRG) and the University of Canterbury are conducting a survey to gather data to help improve our understanding of common tasks and workflows of practicing fire engineers. This will help SFPE identify the fire engineering tools needed to support engineers in the practice of fire engineering, and to identify gaps between the common practices and available practical tools.
>
> Fire engineering tools can include hand calculations, correlations, in-house spreadsheets or software, and free public-domain or commercial software products. We are mainly interested in tools that you use on multiple projects rather than a one-time only tool.
>
> **Participation** The survey is targeted at individuals who are working in fields related to fire safety or fire protection engineering. You must be 18 years or older to take part.
>
> **The survey** You will be asked questions about the fire engineering tools you use. You will also be asked questions about yourself and the work you do.
>
> **Handling of data** It will not be possible to identify you when the data from this survey is presented in reports or papers. Your contact information will not be collected, but some of the collected data relate to you and your employer. However, this data will not be used by the researchers to identify you. The data will always be treated confidentially and will not presented on an individual level.
>
> **Presentation of results** The findings will be published in a report by the researchers for the SFPE Educational & Scientific Foundation. The report will be published on the Foundation's website (https://www.sfpe.org/mpage/FoundationResearch). The researchers may also publish the findings in a scientific paper.
>
> **Voluntary participation** Your participation is voluntary, and you can terminate at any time by closing the browser window. The responses you have entered until you terminate you participation will be used in the project. You will not be offered reimbursement for your participation.
>
> **Responsible researcher** This survey is being conducted by researchers at the Fire Research Group Ltd and the University of Canterbury.
> Prof. Daniel Nilsson is the responsible researcher. You can contact Daniel by

phone (+64 (0) 33690329) or email (Daniel.Nilsson@canterbury.ac.nz). Daniel will be pleased to discuss any concerns you may have about participation.

Ethics approval This project has been reviewed and approved by the University of Canterbury Human Ethics Committee (HEC 2020/73/LR-PS), and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

4.2 Sampling and demographics of the survey respondents

Data was collected over the period from February 9 to June 7, 2021. A total of 156 people from 32 countries agreed to complete the survey. Given a sample size from an estimated population of 4672 SFPE members (as at June 2021), and based on a standard deviation of 0.5 and confidence interval of 90%, we estimate the margin of error to be 6.6% [10].

The survey respondents were asked - *What country are you currently employed in?* with most respondents employed in the USA (33%) followed by New Zealand (12%), Canada (8%), Australia (6%) and United Kingdom (6%). The results are summarised as shown in Figure 1 with the complete listing of countries shown in Figure 2.

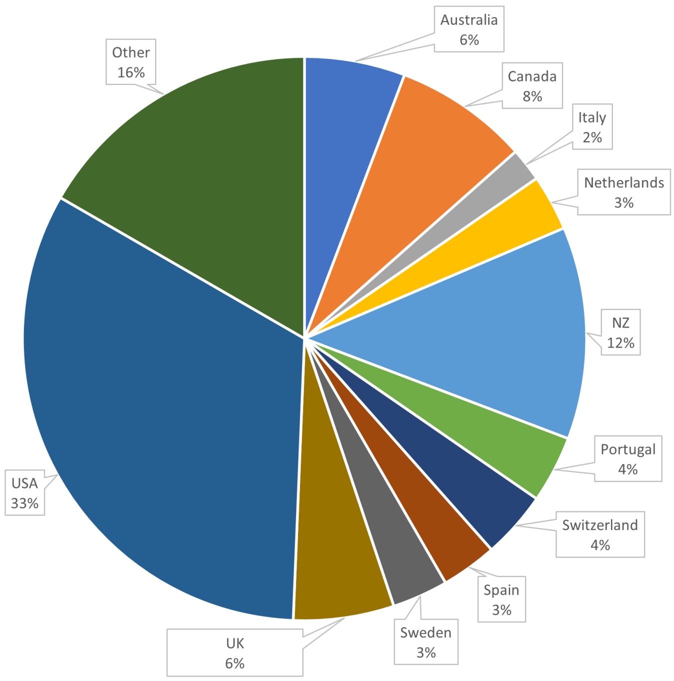

Figure 1. Most common country survey respondents currently employed in.

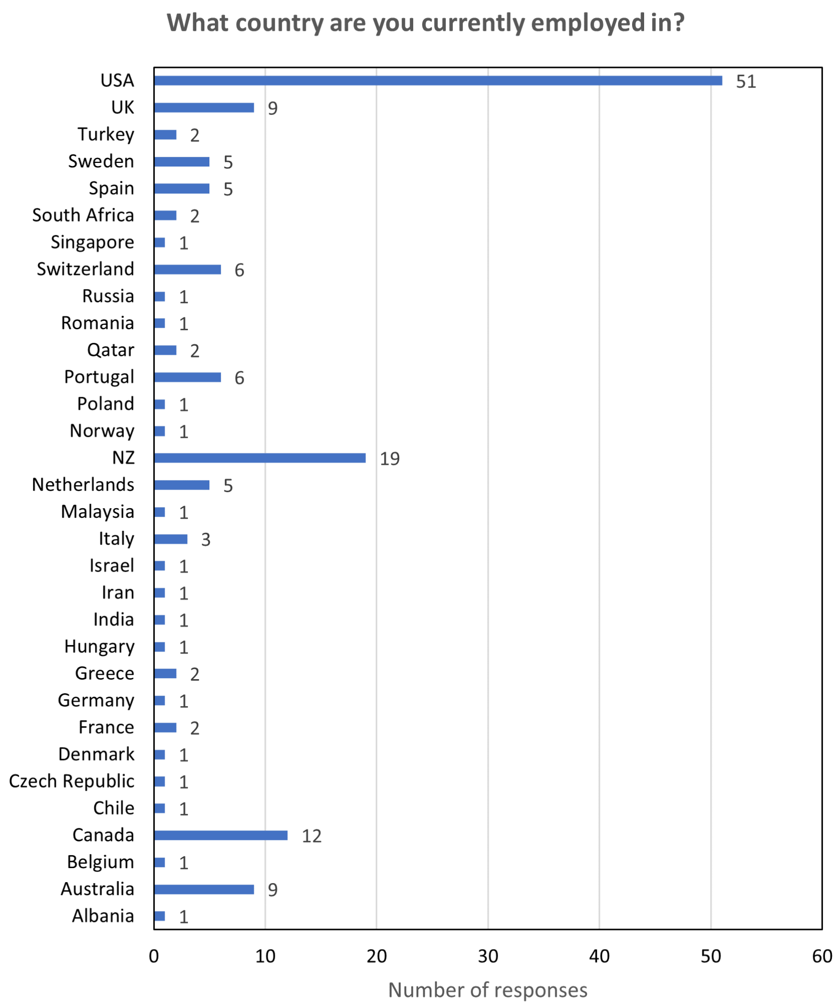

Figure 2. Country survey respondents currently employed in.

It is likely that New Zealand is over-represented in the results due to the research team being based in New Zealand with more respondents who may have known the research team members and hence being more willing to participate in the survey. This is confirmed in Figure 3 showing New Zealand is over-represented by a factor of about 6 whereas the USA is under-represented by a factor of about 2. In our view, this would have led to a slightly different ranking of the use of some of individual models, however we do not believe it would significantly affect the overall findings and recommendations from the survey. While there are differences in model selection in different countries, the gaps and future needs identified are likely to be relevant for all countries represented within SFPE.

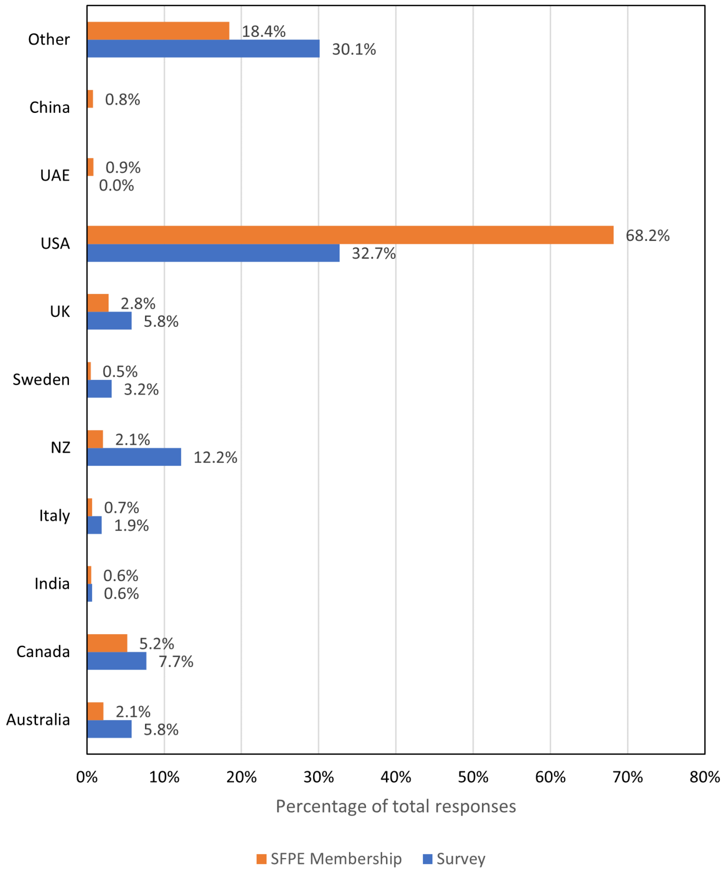

Figure 3. Country survey respondents currently employed in compared with SFPE membership data.

The survey respondents were asked - *How old are you?* with most respondents falling in the band 35 - 45 years (31%). The results are shown in Figure 4.

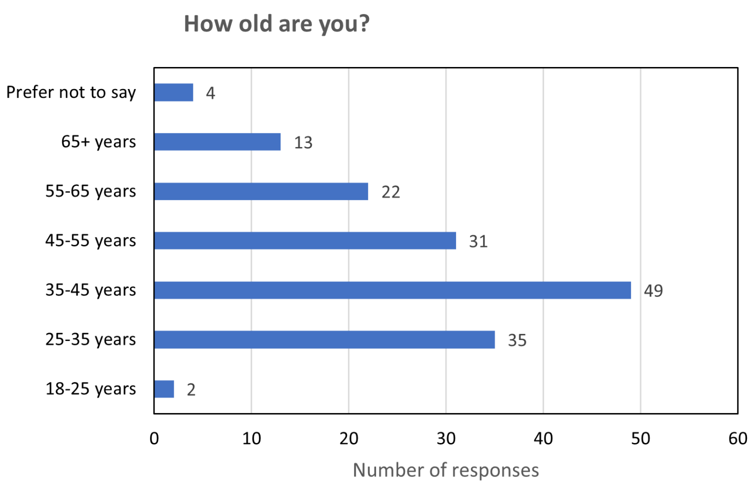

Figure 4. Age of survey respondents.

The survey respondents were asked - *How many years of work experience do you have in fire-related positions?* with most respondents replying 15+ years (54%). The results are shown in Figure 5.

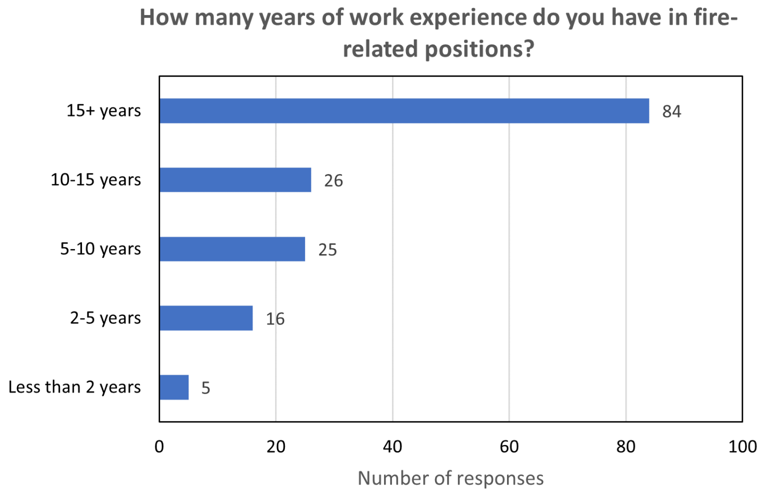

Figure 5. Fire-related work experience of survey respondents.

The survey respondents were asked - *What qualifications do you have?* with 17% having a PhD, 62% having a Masters Degree and 53% having a Bachelor or undergraduate degree. The results are shown in Figure 6. Multiple selections were permitted.

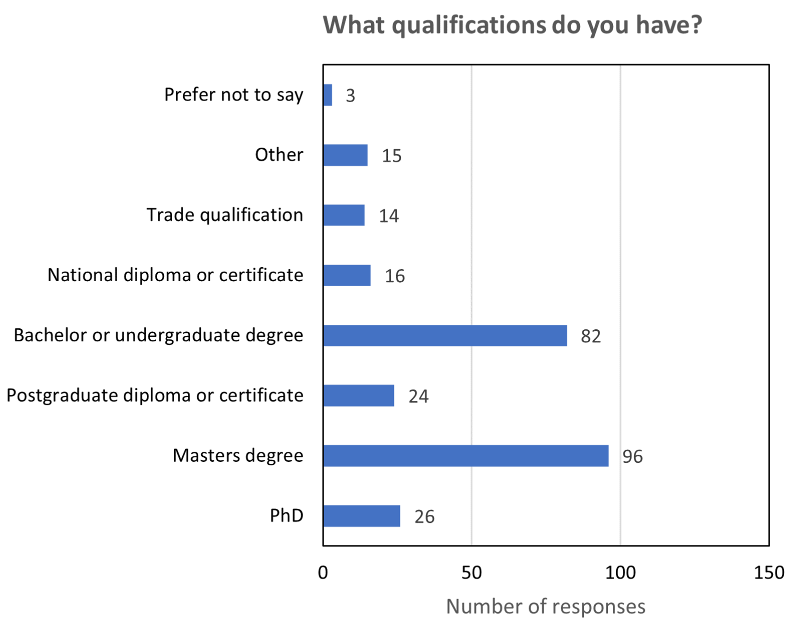

Figure 6. Qualifications held by survey respondents.

The survey respondents were asked - *What is your gender?* with most respondents being male (91%) as shown in Figure 7. Females, who comprise 11% of the SFPE membership as at June 2021 were slightly under-represented at 8%. 1% of respondents preferred not to say, while none identified as non-binary.

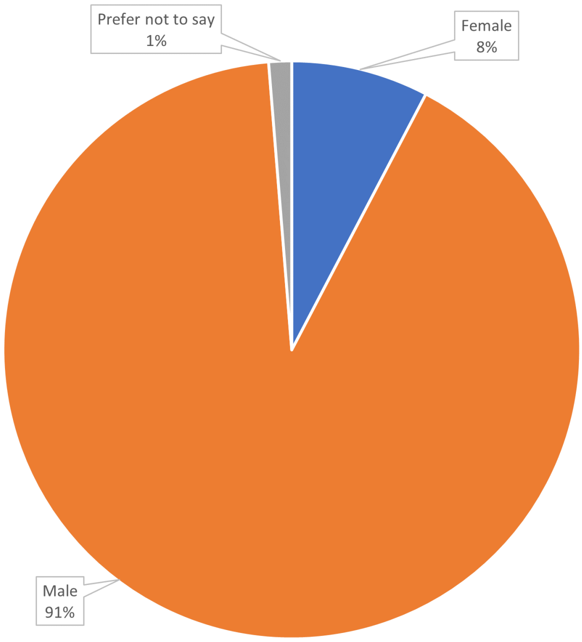

Figure 7. Gender of survey respondents.

The survey respondents were asked - *Are you an SFPE member?* with most respondents replying yes (70%) as shown in Figure 8. Although not all respondents were SFPE members, we do not think that this would necessarily bias the results in any significant way.

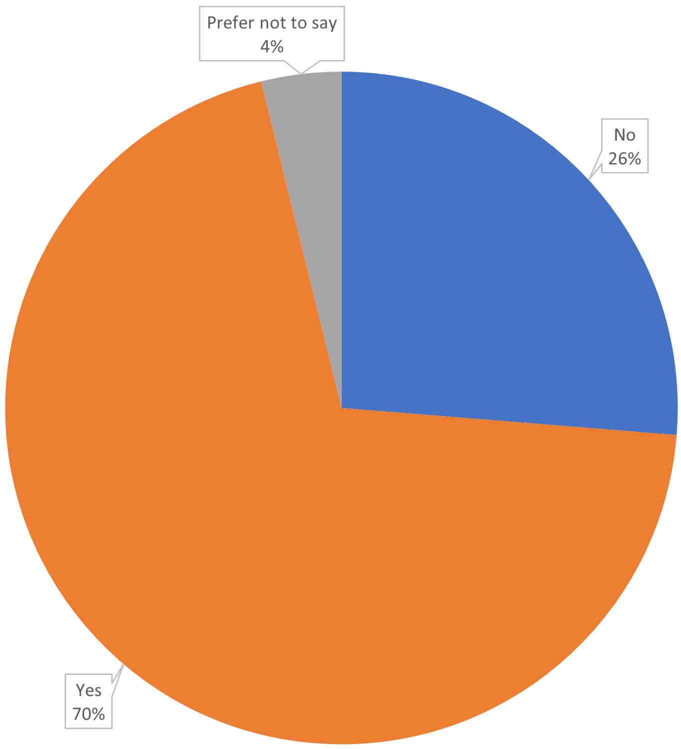

Figure 8. SFPE membership of survey respondents.

The survey respondents were asked - *What sector(s) do you represent?* Multiple selections were permitted but in this case they were split equally among the selected sectors (i.e, if a respondent indicated they worked in both design and education sectors then a count of 0.5 was contributed for each of those sectors for that respondent).

The options were given as:

- Producer - an individual who represents an organization (or trade association) that manufactures or markets products
- Design - an individual who produces drawings, diagrams, specifications or calculations for construction in the built environment (consultants, architectural/engineering firms)
- Construction - an individual involved in construction or product installation in the built environment
- Research, education and testing - an individual who represents public or private sector organizations involved in research, standards development, education or testing.
- Facilities - an individual having a legal interest in a property, building, or structure (facility manager, owner representative)
- Insurance - a representative of an insurance company, broker, agent, bureau, or inspection agency
- Enforcement, inspection, standards or regulation

- Fire and rescue services - with non-enforcement duties, firefighting, safety
- Other - an individual with expert knowledge who is not described by one of the categories above, please specify

Most respondents worked in the design sector (63%), followed by the research, testing and education sector (9%) as shown in Figure 9.

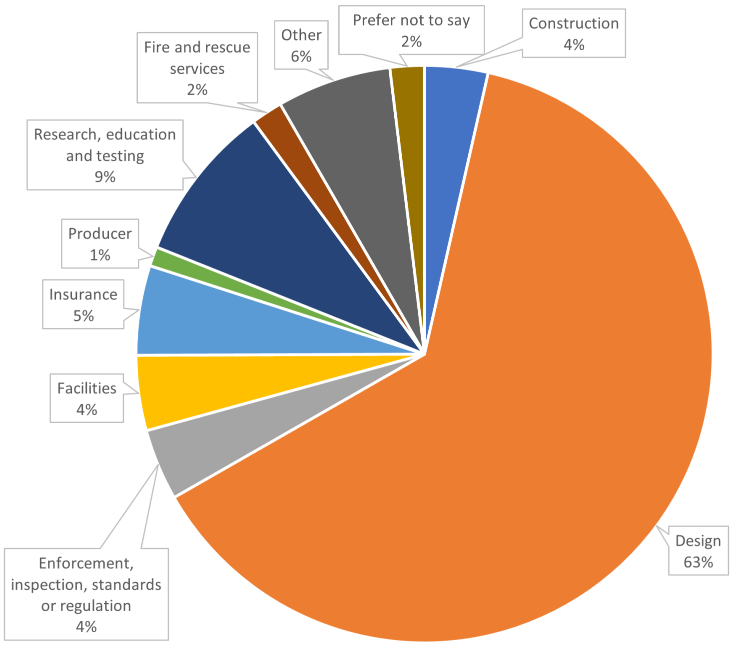

Figure 9. Industry sectors worked in by survey respondents.

4.3 Information requested

The survey was divided into five parts:

4.3.1 Part 1 - The tools

Part 1 concerned current use of fire engineering tools in the areas of:

- Egress
- Fire and/or smoke development and spread (including tenability, ignition, smoke management, radiation, etc)
- Data pre/postprocessing, visualization
- Hydraulic flows
- Detection, suppression system design
- Risk analysis

- Information management, drawings (including BIM, CAD, etc),
- Response to elevated temperatures (including structures and nonstructural components and systems)
- Fire service intervention, tactics, operations
- Other

For each of these areas, respondents were asked to identify the tools that they used and to describe:

- The problem/aspect they were investigating with the tool.
- How often they used the fire engineering tool.
- What changes or improvements (if any) would they suggest to the tool.

4.3.2 Part 2 - Calculation platforms

Part 2 concerned the platforms used for calculations.

- What computing resources or devices are used to run fire engineering tools and how often.
- What computing resources or devices are preferred to be used in the future.

4.3.3 Part 3 - Influence of the AHJ on tool selection

Part 3 concerned the influence of the AHJ on the selection of fire engineering tools and respondents were asked if they were aware of any specific fire engineering tools required by the approving authority or regulator for projects they completed.

4.3.4 Part 4 - Current gaps and future needs

Part 4 concerned the future needs of fire engineering practitioners and respondents were asked what gaps exist in current fire engineering tools or what new tools should be developed.

4.3.5 Part 5 - Demographics

Part 5 sought to obtain information regarding the background, experience and general demographics of the respondents as previously presented in subsection 4.2.

5. Survey Results

5.1 Types of calculations done

Survey respondents were asked - *Have you used any fire engineering tools in the last 2 years?* with 92% indicating yes as shown in Figure 10. In the event the respondent replied no to this question, they were not asked any further questions regarding the types of calculation and specific tools used. The period of two years was selected as it was thought that the capability of individual tools would not have greatly changed over that period and for the feedback provided regarding specific tools to be considered current.

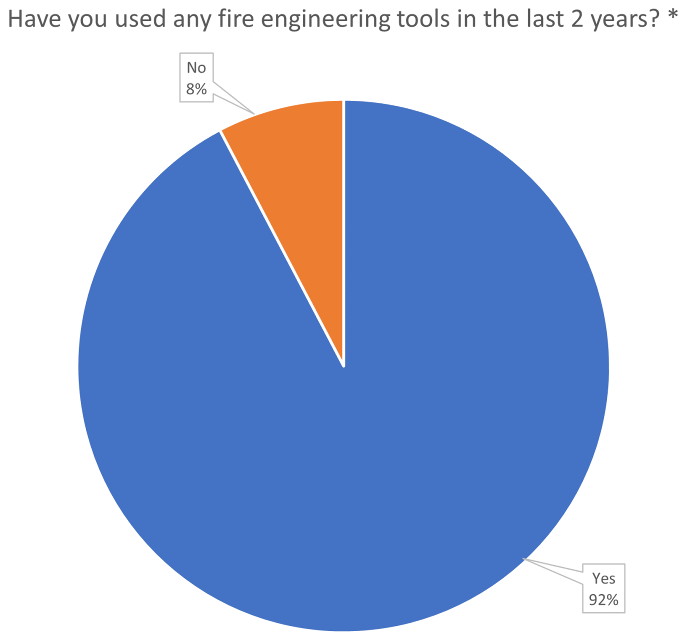

Figure 10. Survey respondents who had used fire engineering tools in the past 2 years.

Survey respondents were then asked - ”In which of the following areas have you used fire engineering tools?”. The options were given as:

- Egress
- Fire and/or smoke development and spread (including tenability, ignition, smoke management, radiation, etc)
- Response to elevated temperatures (including structures and nonstructural components and systems)
- Fire service intervention, tactics, operations
- Risk analysis
- Hydraulic flows, detection, suppression system design
- Information management, drawings (including BIM, CAD, etc)

- Data pre/postprocessing, visualization
- Other (you will be able to provide an explanation later)

The results are shown in Figure 11, with the top three topics being 1) fire/smoke development and spread, 2) egress and 3) information management, respectively. Multiple selections were permitted.

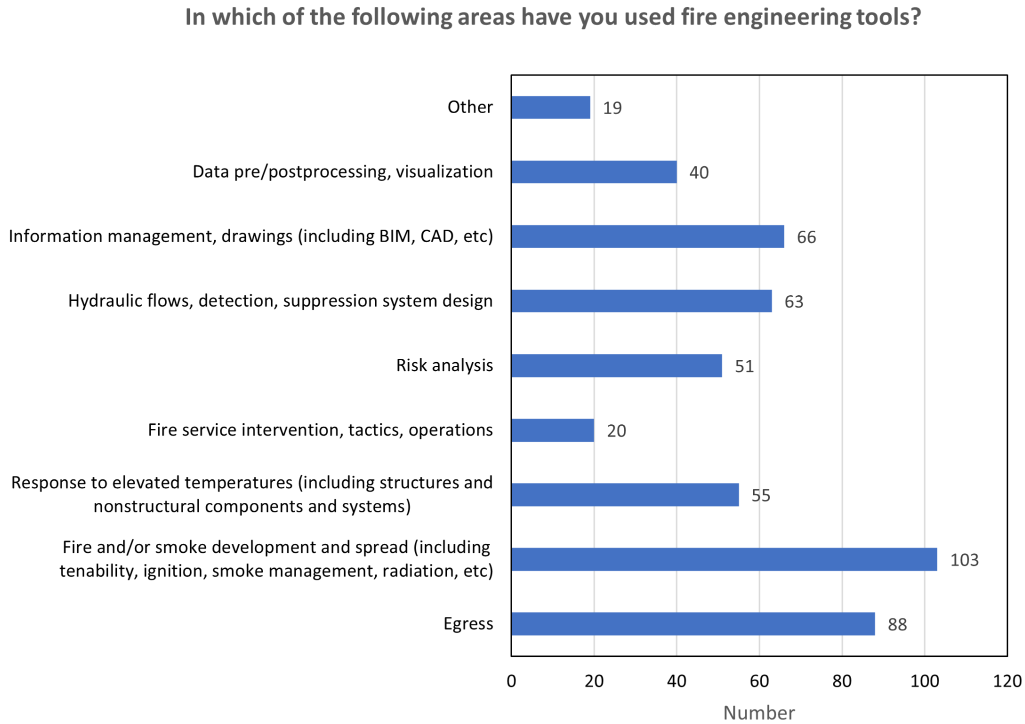

Figure 11. Topic areas where survey respondents use fire engineering tools.

5.2 Fire engineering tools in use

5.2.1 Overview

The survey respondents were asked about their current use of fire engineering tools in each of the areas previously shown in Figure 11. For each area they selected, they were permitted to describe up to five different tools. Figure 12 shows the tools listed across all areas ranked by the number of respondents who had mentioned that particular tool. Only tools that were mentioned by at least two different respondents are included in this figure. There were a range of additional tools mentioned but only by one respondent.

In order not to prompt or bias any user response toward any particular tool, the respondent was asked to describe their tools in free-text fields. Subsequent post-processing by the research team was done to aggregate the replies as required where the tools were described or spelt slightly differently.

The top ten most common software programs mentioned, excluding various spreadsheet and in-house tools, were Fire Dynamics Simulator (FDS), Pathfinder, Pyrosim, AutoCAD, CFAST, Revit, B-RISK, Smokeview, HASS and FireWind.

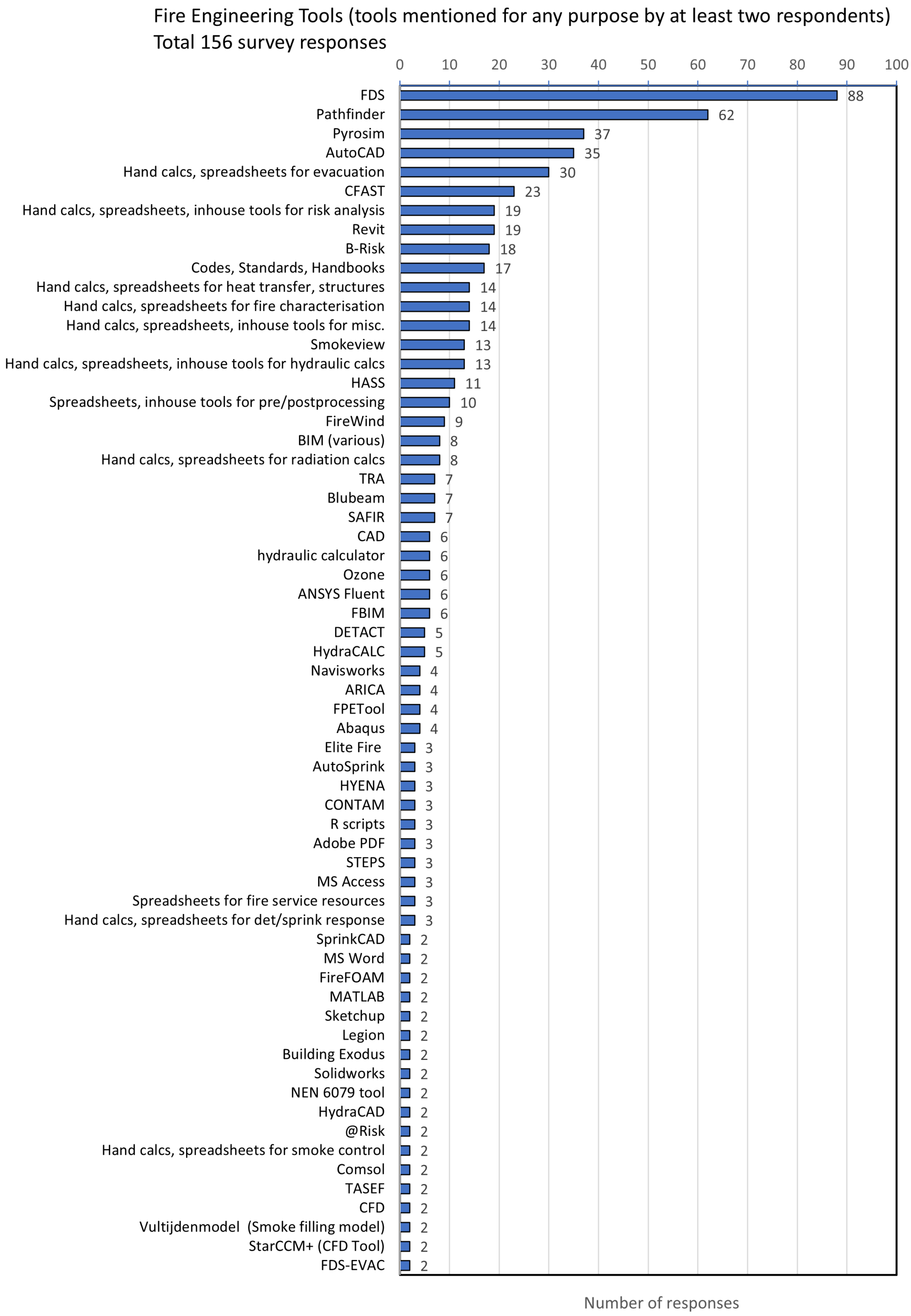

Figure 12. Fire engineering tools mentioned by at least two survey respondents.

Figure 13 to Figure 20 show the tools mentioned by the respondents in each of the different topic areas listed in subsection 5.1.

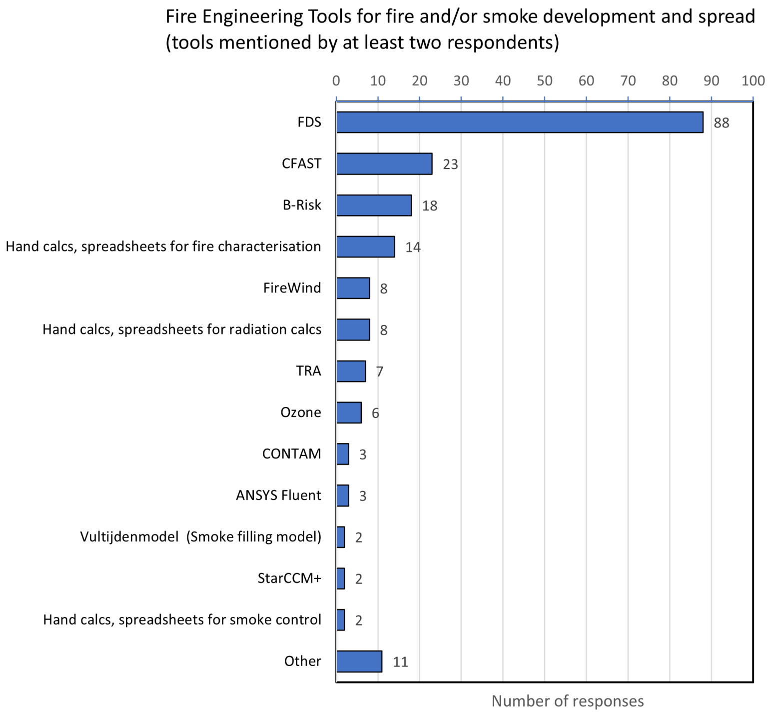

Figure 13. Fire engineering tools for fire and/or smoke development and spread (including tenability, ignition, smoke management, radiation, etc) mentioned by at least two survey respondents.

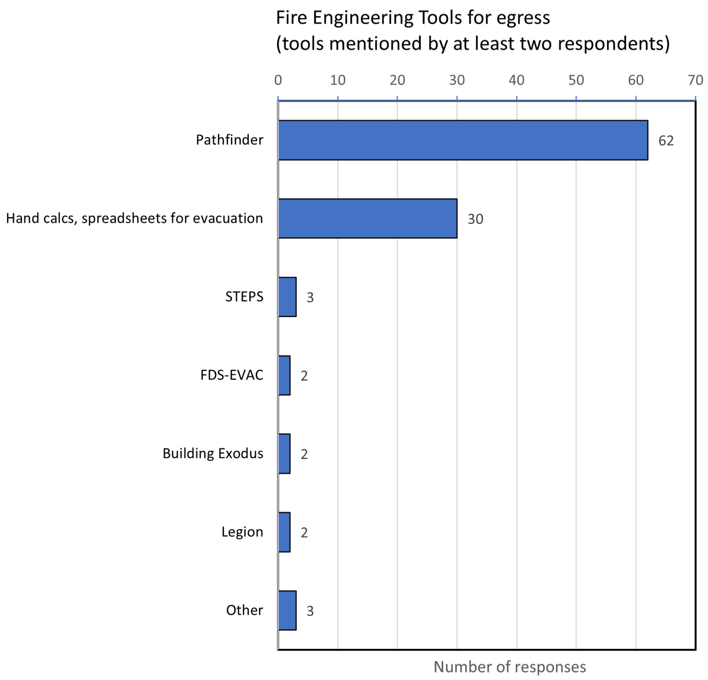

Figure 14. Fire engineering tools for egress mentioned by at least two survey respondents.

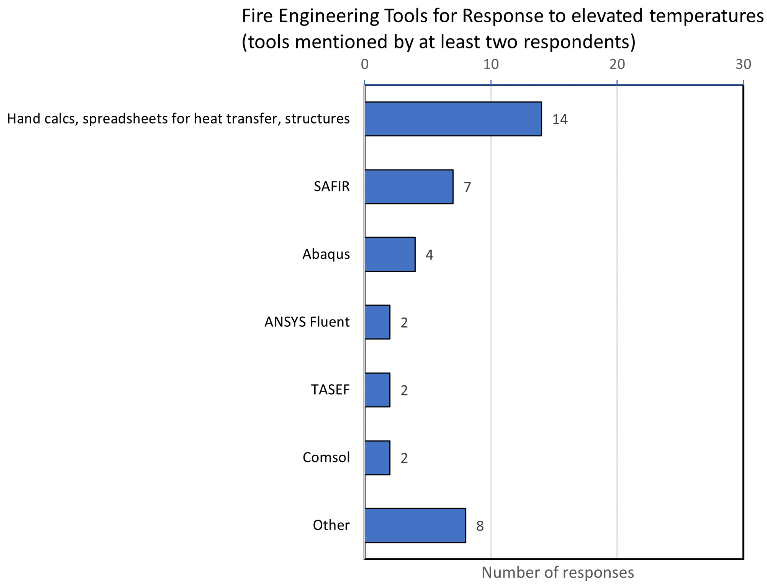

Figure 15. Fire engineering tools for response to elevated temperatures (including structures and nonstructural components and systems) mentioned by at least two survey respondents.

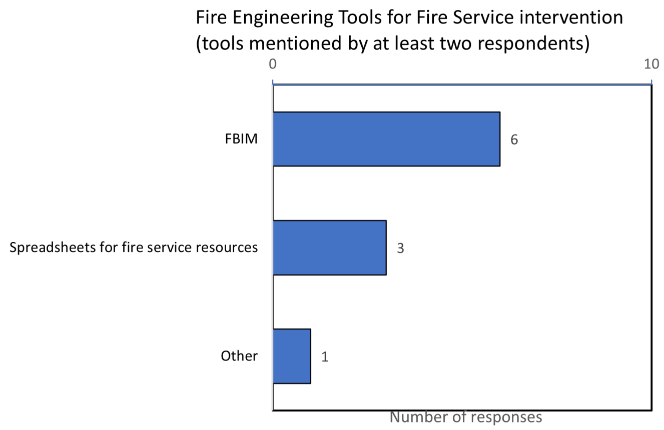

Figure 16. Fire engineering tools for fire service intervention, tactics, operations mentioned by at least two survey respondents.

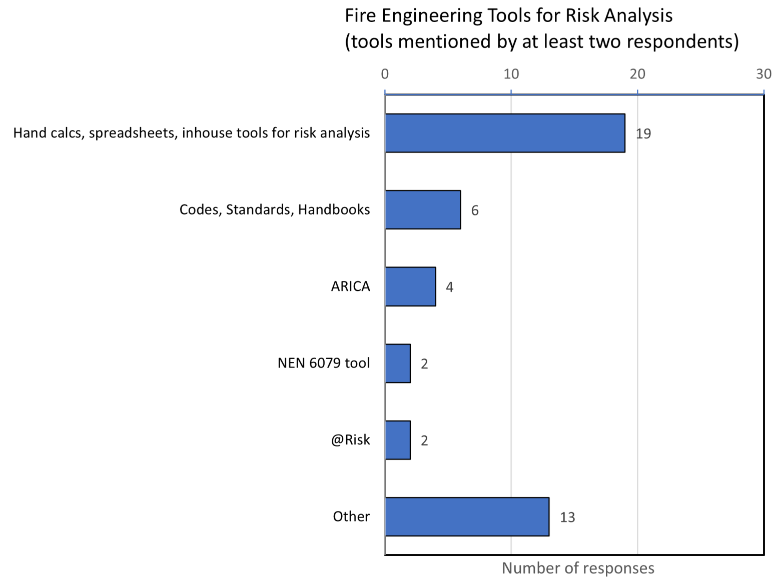

Figure 17. Fire engineering tools for risk analysis mentioned by at least two survey respondents.

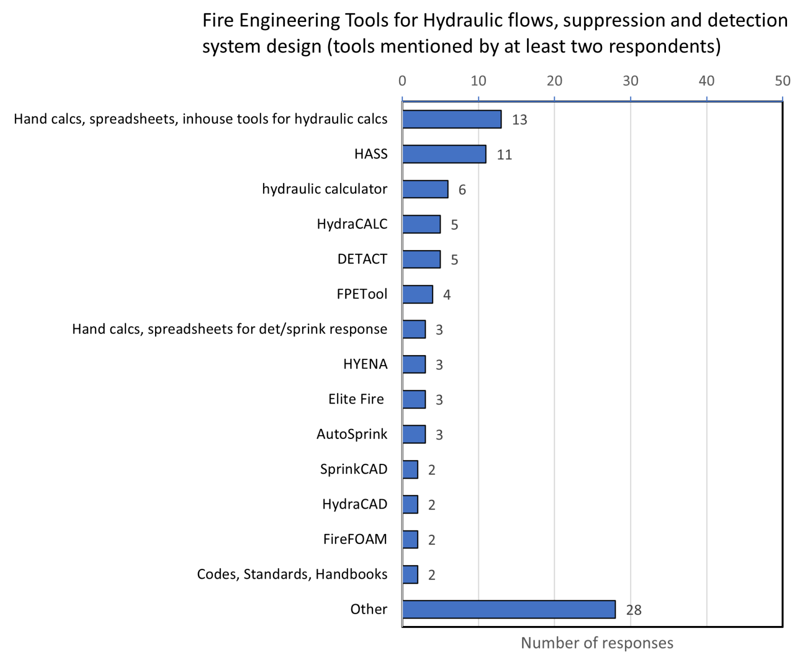

Figure 18. Fire engineering tools for hydraulic flows, detection, suppression system design mentioned by at least two survey respondents.

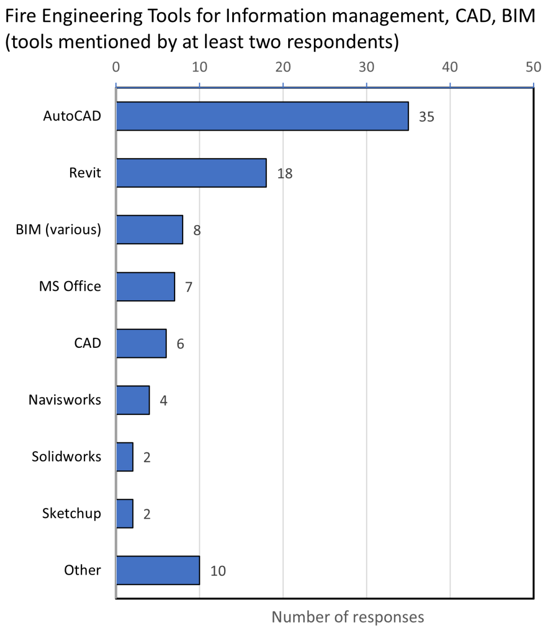

Figure 19. Fire engineering tools for information management, drawings (including BIM, CAD, etc) mentioned by at least two survey respondents.

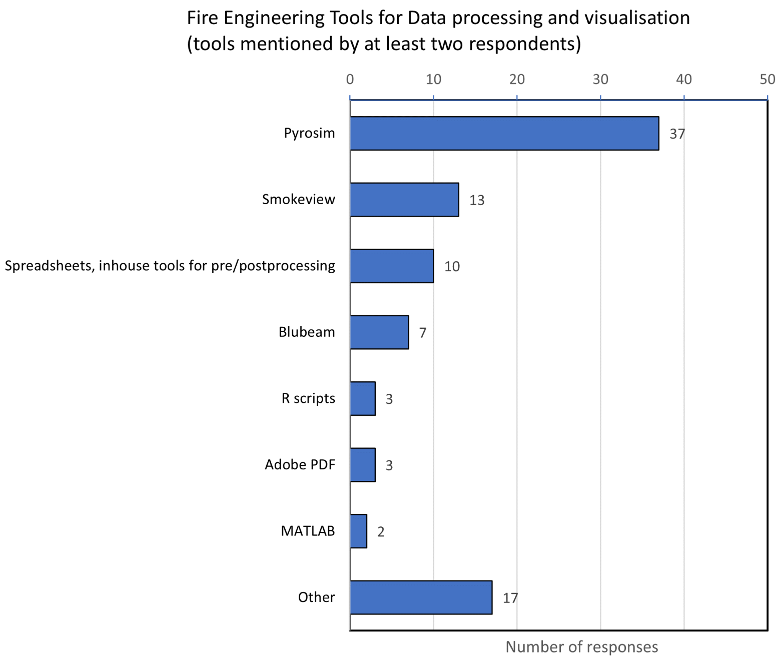

Figure 20. Fire engineering tools for data pre/postprocessing, visualization mentioned by at least two survey respondents.

The following subsections provide a summary of the feedback provided by the respondents in relation to the individual tools that they identified. Only the top ten most commonly named and generic tools have been included here.

5.2.2 Fire Dynamics Simulator, FDS

This section presents survey data collected that was specific to Fire Dynamics Simulator (FDS). This is a CFD fire model developed at NIST, USA with further details provided in subsubsection 7.2.2. The model use in different countries is summarised in Figure 21 and the frequency of use by the 88 respondents who identified the tool is shown in Figure 22. Most users of FDS were from the USA (30%), followed by New Zealand (11%) and Australia (9%). However, the proportion of respondents from each of these countries mentioning FDS were 51%, 53% and 89% respectively.

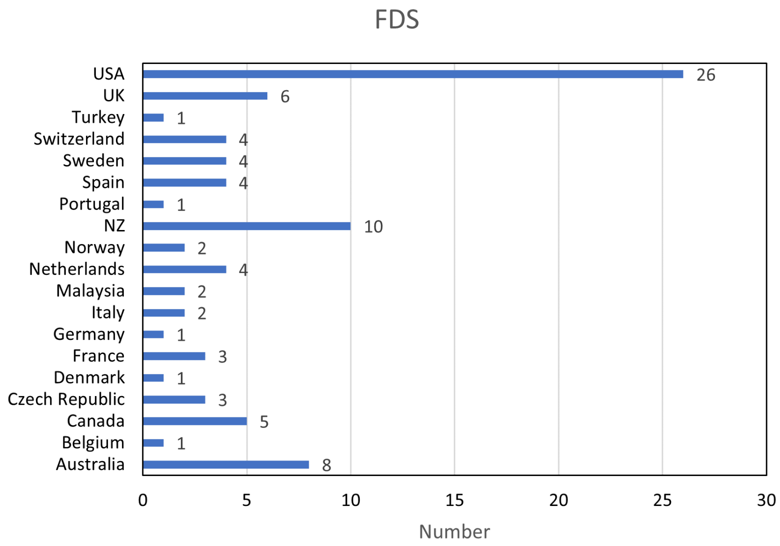

Figure 21. FDS usage by country.

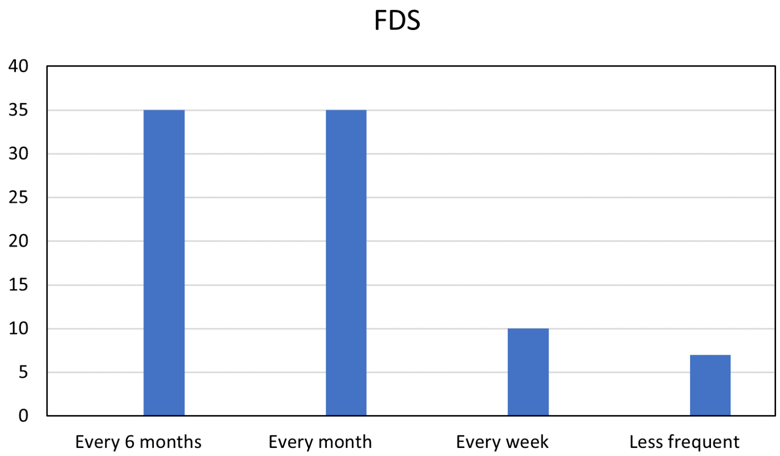

Figure 22. FDS frequency of use.

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Detailed responses to this question are contained in subsection A.1.

5.2.3 Pathfinder

This section presents survey data collected that was specific to Pathfinder. This is an agent based evacuation fire model developed by Thunderhead Engineering, USA with further details provided in subsubsection 7.1.2. The model use in different countries is summarised in Figure 23 and the frequency of use by the 62 respondents who identified the tool is shown in Figure 24. Most users of Pathfinder were from New Zealand (23%), followed by the USA (19%) and Australia (8%). However, the proportion of respondents from each of these countries mentioning Pathfinder were 74%, 24% and 56% respectively.

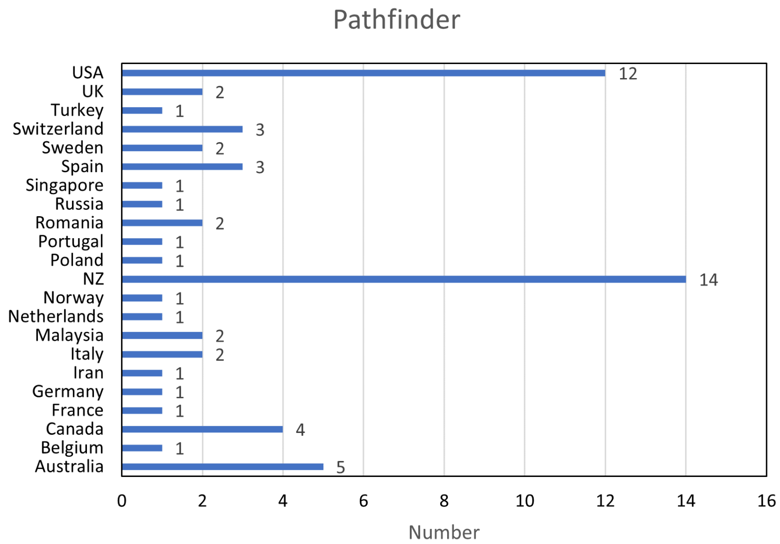

Figure 23. Pathfinder usage by country.

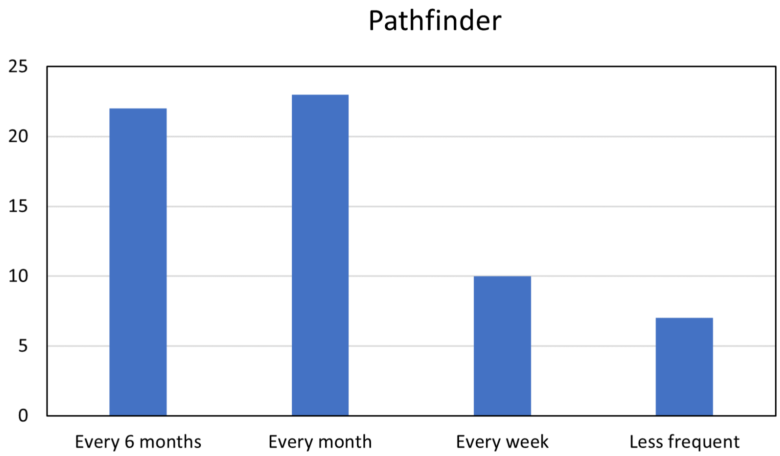

Figure 24. Pathfinder frequency of use.

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Detailed responses to this question are contained in subsection A.2.

5.2.4 Pyrosim

This section presents survey data collected that was specific to Pyrosim. This is a user interface and data processing tool for use with FDS and developed by Thunderhead Engineering, USA with further details provided in subsubsection 7.5.2. The model use in different countries is summarised in Figure 25 and the frequency of use by the 37 respondents who identified the tool is shown in Figure 26. Most users of Pyrosim were from New Zealand (19%), followed by the Italy (11%) and Canada (11%). However, the proportion of respondents from each of these countries mentioning Pyrosim were 37%, 53% and 33% respectively.

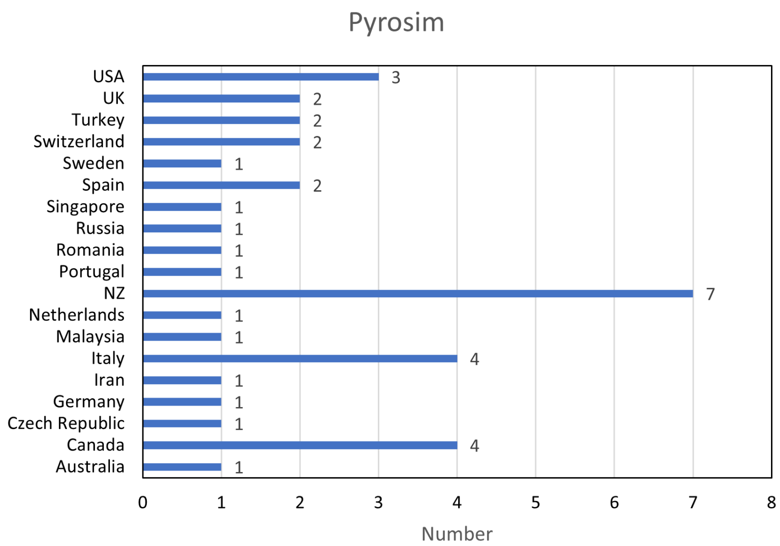

Figure 25. Pyrosim usage by country.

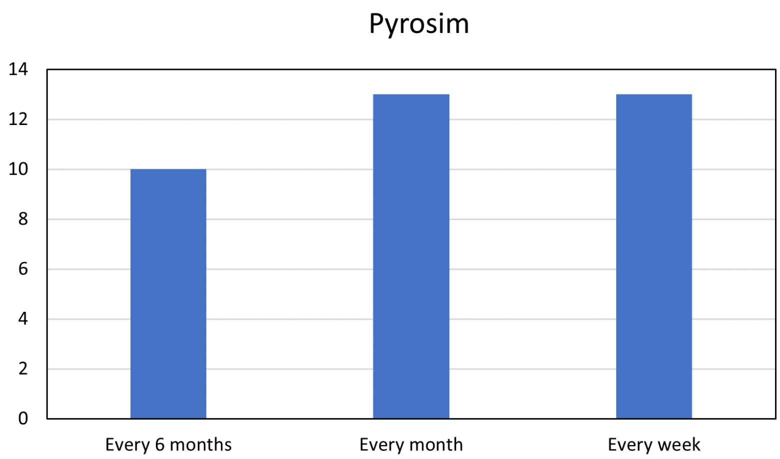

Figure 26. Pyrosim frequency of use.

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Detailed responses to this question are contained in subsection A.3.

5.2.5 AutoCAD

This section presents survey data collected that was specific to AutoCAD. This is a CAD tool developed by Autodesk with further details provided in subsubsection 7.6.4. The model use in different countries is summarised in Figure 27 and the frequency of use by the 35 respondents who identified the tool is shown in Figure 28. Most users of AutoCAD were from the USA (34%), followed by the Portugal (11%) and Switzerland (9%). However, the proportion of respondents from each of these countries mentioning AutoCAD were 24%, 67% and 50% respectively.

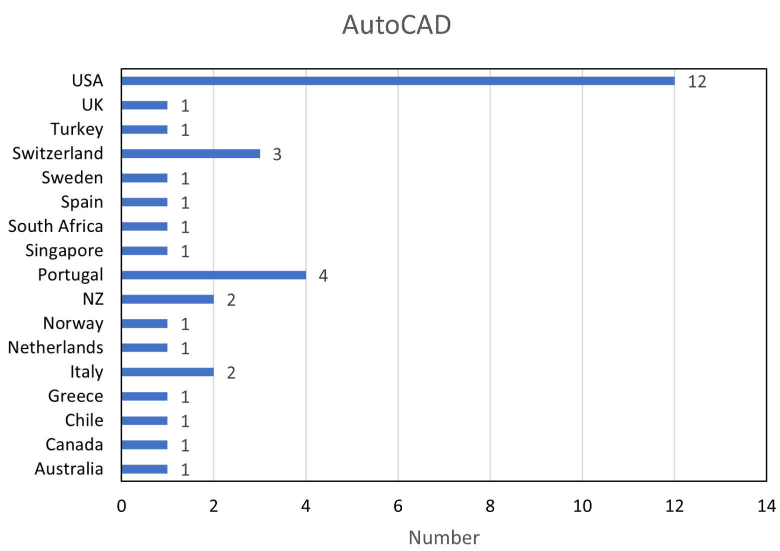

Figure 27. AutoCAD usage by country.

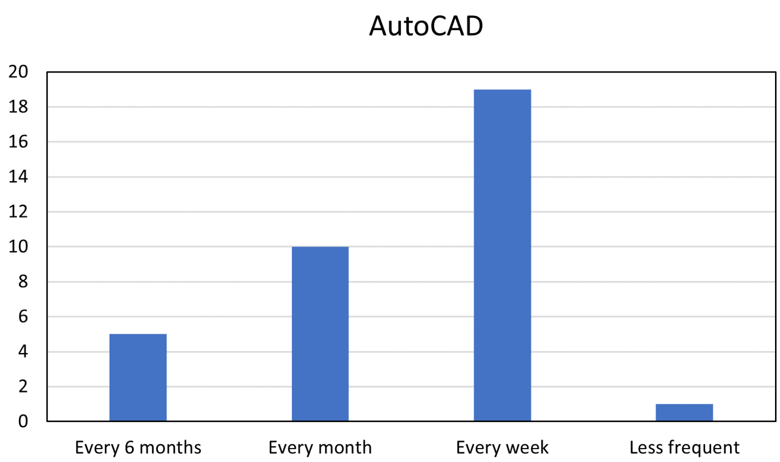

Figure 28. AutoCAD frequency of use.

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Detailed responses to this question are contained in subsection A.4.

5.2.6 Hand calculations, spreadsheets for evacuation

This section presents survey data collected that was specific to various hand calculations and spreadsheets used for evacuation. There were 30 respondents who mentioned they used calculations of this type. Use in different countries is summarised in Figure 29 and the frequency of use by the 35 respondents who identified the tool is shown in Figure 30. Most users of hand calculations and spreadsheets for evacuation were from the New Zealand (23%), followed by the USA (17%) and UK (10%). However, the proportion of respondents from each of these countries mentioning hand calculations and spreadsheets used for evacuation were 37%, 10% and 33% respectively.

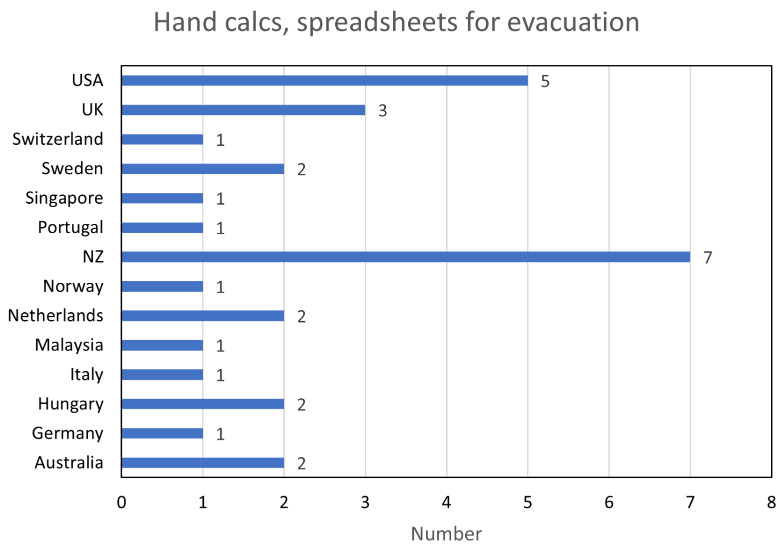

Figure 29. Hand calculations, spreadsheets for evacuation usage by country.

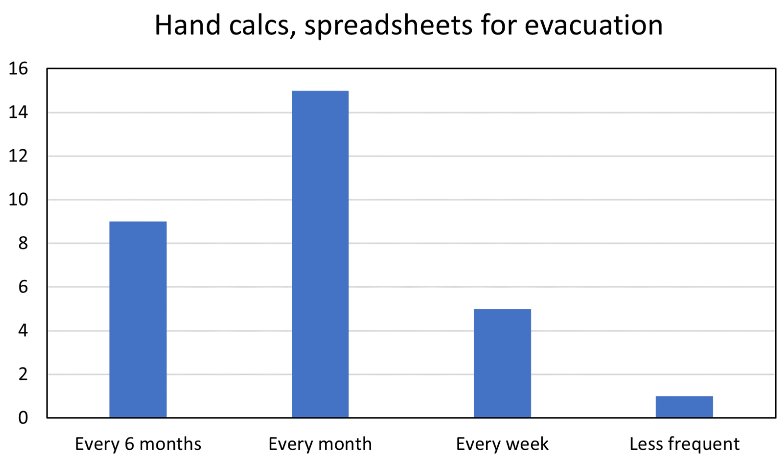

Figure 30. Hand calculations, spreadsheets for evacuation frequency of use.

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Detailed responses to this question are contained in subsection A.5.

5.2.7 CFAST

This section presents survey data collected that was specific to CFAST. This is a fire zone model developed by NIST, USA with further details provided in subsubsection 7.2.4. The model use in different countries is summarised in Figure 31 and the frequency of use by the 23 respondents who identified the tool is shown in Figure 32. Most users of CFAST were from Australia (17%), Netherlands (17%) followed by the USA (13%) and Italy (13%). However, the proportion of respondents from each of these countries mentioning CFAST were 44%, 80%, 6% and 100% respectively.

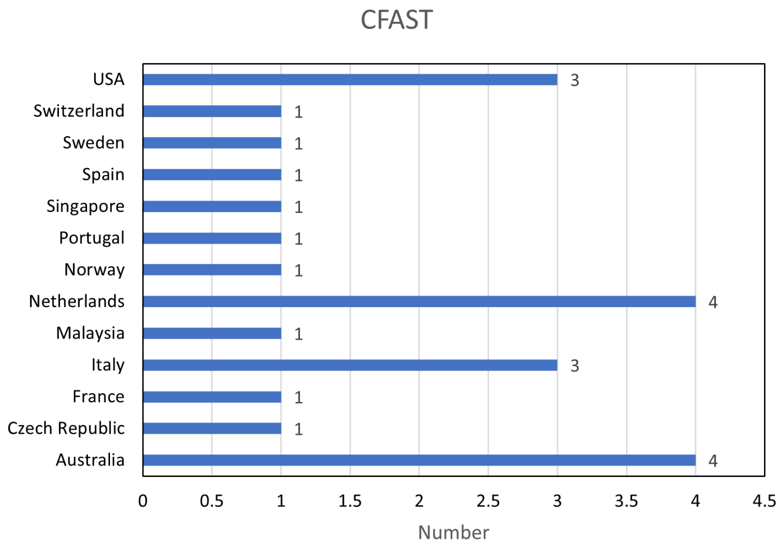

Figure 31. CFAST usage by country.

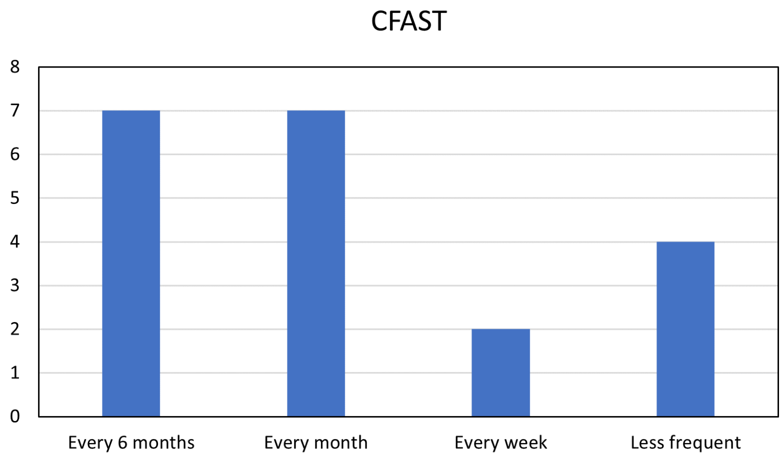

Figure 32. CFAST frequency of use.

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Detailed responses to this question are contained in subsection A.6.

5.2.8 Revit

This section presents survey data collected that was specific to Revit. This is a BIM tool developed by Autodesk with further details provided in subsubsection 7.6.2. The model use in different countries is summarised in Figure 33 and the frequency of use by the 19 respondents who identified the tool is shown in Figure 34. Most users of Revit were from the USA (47%), followed by New Zealand (21%). However, the proportion of respondents from each of these countries mentioning Revit were 18%, and 21% respectively.

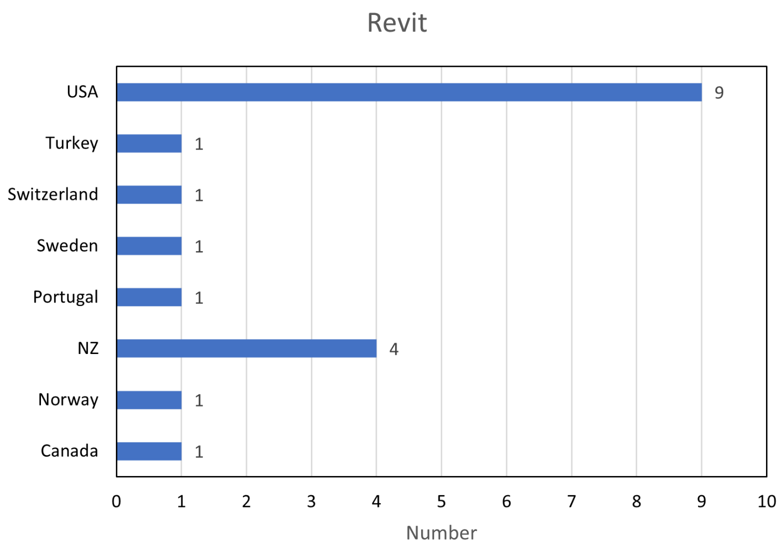

Figure 33. Revit usage by country.

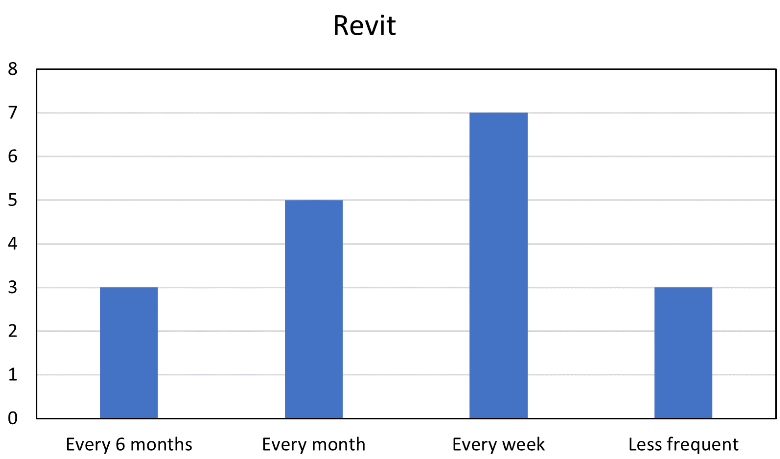

Figure 34. Revit frequency of use.

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Detailed responses to this question are contained in subsection A.7.

5.2.9 Hand calcs, spreadsheets, inhouse tools for risk analysis

This section presents survey data collected that was specific to hand calculations, spreadsheets, and inhouse tools used for risk analysis. There were 19 respondents who mentioned they used calculations of this type. Use in different countries is summarised in Figure 35 and the frequency of use by the 35 respondents who identified the tool is shown in Figure 36. Most users of hand calculations and spreadsheets for evacuation were from the USA (37%), followed by Australia (16%) and Switzerland (11%). However, the proportion of respondents from each of these countries mentioning hand calculations and spreadsheets used for risk analysis were 14%, 33% and 33% respectively.

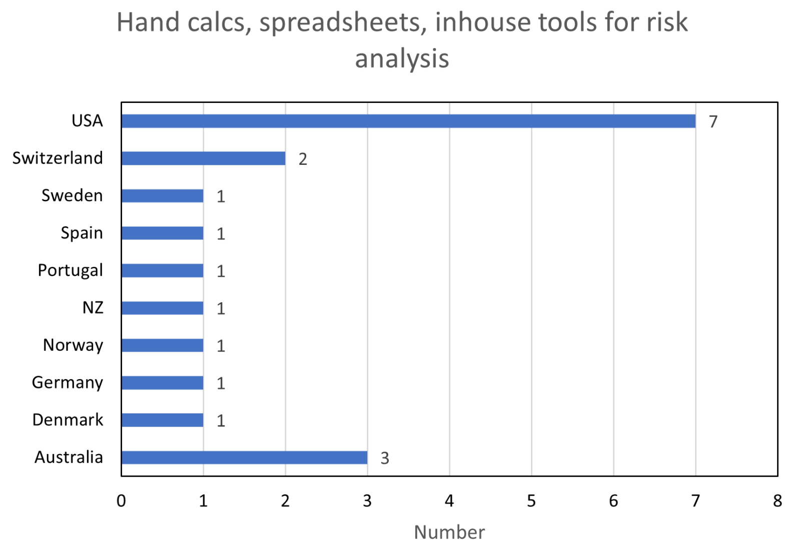

Figure 35. Hand calcs, spreadsheets, inhouse tools for risk analysis usage by country.

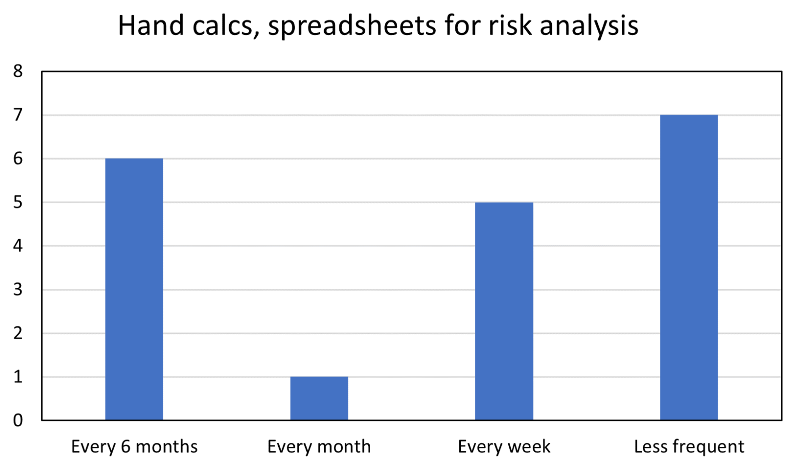

Figure 36. Hand calcs, spreadsheets, inhouse tools for risk analysis frequency of use.

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Detailed responses to this question are contained in subsection A.8.

5.2.10 B-RISK

This section presents survey data collected that was specific to B-RISK. This is a fire zone model developed by BRANZ, New Zealand with further details provided in subsubsection 7.2.5. The model use in different countries is summarised in Figure 37 and the frequency of use by the 18 respondents who identified the tool is shown in Figure 38. Most users of B-RISK were from New Zealand (78%) followed by the UK (11%) and Canada (11%). However, the proportion of respondents from each of these countries mentioning B-RISK were 74%, 22% and 17% respectively. We have previously noted that New Zealand was over-represented in the survey sampling compared to the general SFPE membership by country. This means the use of the B-RISK fire model overall is also over-represented in the survey because it is mainly used in New Zealand.

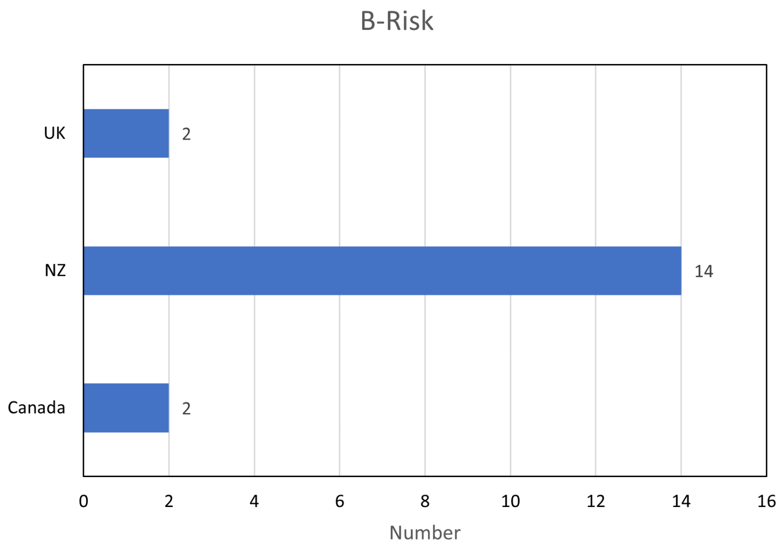

Figure 37. B-RISK usage by country.

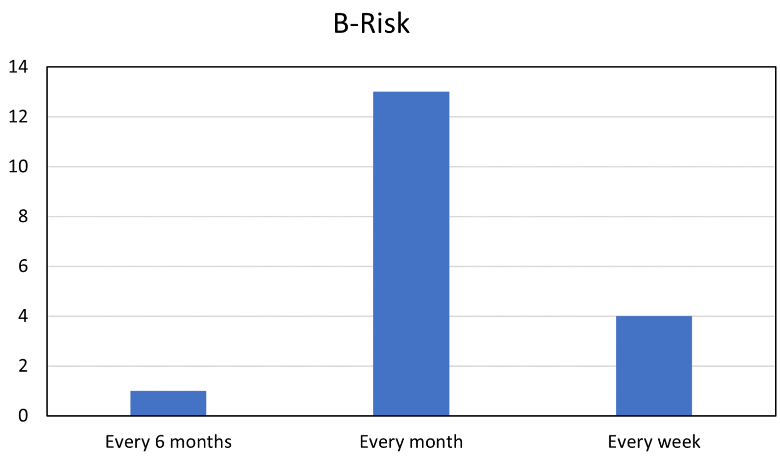

Figure 38. B-RISK frequency of use.

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Detailed responses to this question are contained in subsection A.9.

5.2.11 Codes, standards and handbooks

This section presents survey data collected that was specific to the use of codes, standards and handbooks. While we did not anticipate codes and handbooks would be mentioned as a 'tool' various respondents mentioned them and so they are included here.

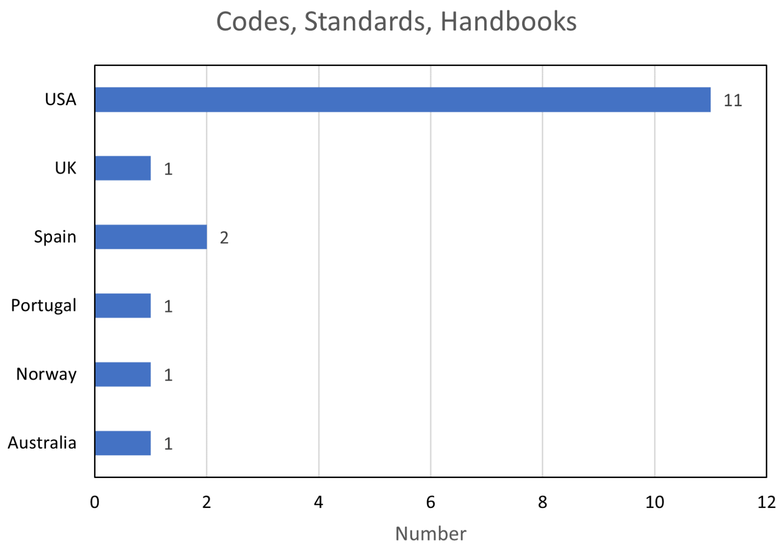

Figure 39. Codes, Standards, Handbooks usage by country.

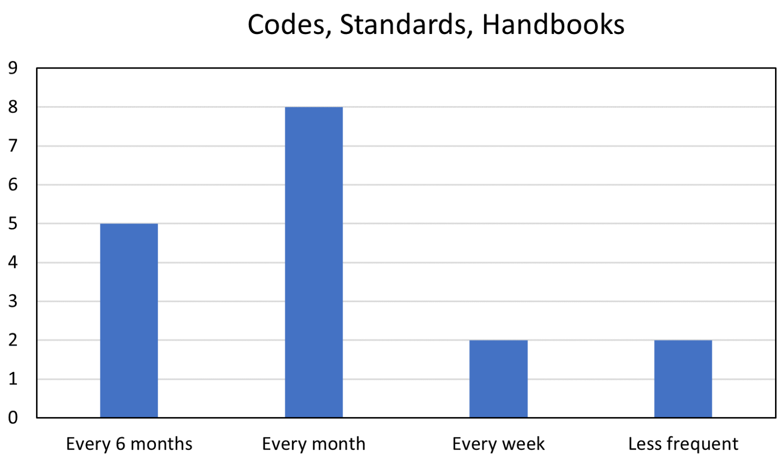

Figure 40. Codes, Standards, Handbooks frequency of use.

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Detailed responses to this question are contained in subsection A.10.

5.3 Calculation platforms

The survey respondents were asked - *What computing resources or devices do you use to run your fire engineering tools and how often?* with the results summarised in Figure 41 to Figure 45. The most common platform used on a weekly basis was a local personal computer (64%) followed by inhouse computer clusters (31%), websites (10%), tablets or phones (11%) and third-party computing clusters the least commonly used on a weekly basis (6%).

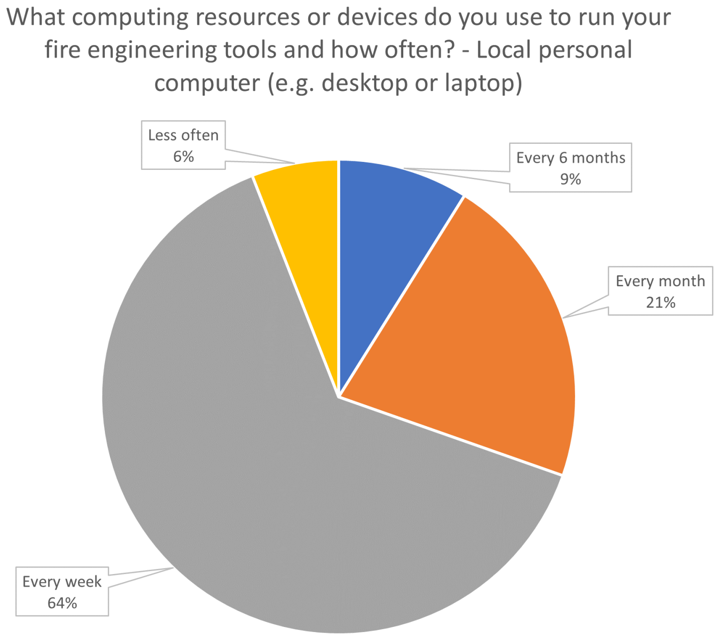

Figure 41. Frequency of use - local personal computer.

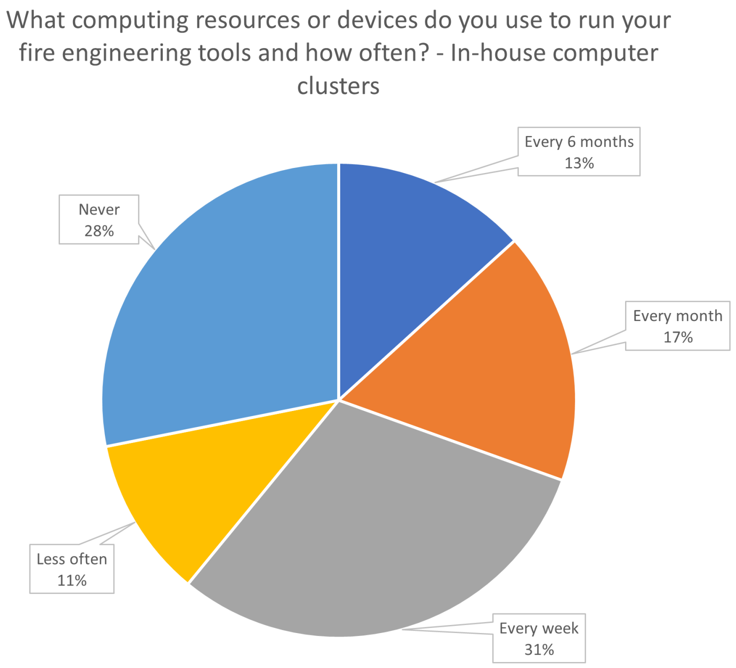

Figure 42. Frequency of use - inhouse computer clusters.

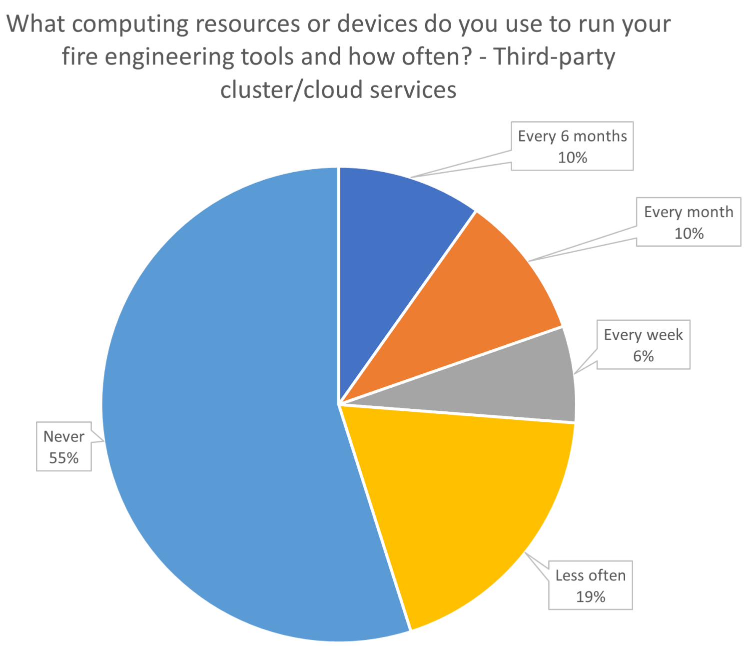

Figure 43. Frequency of use - third party cluster/cloud services.

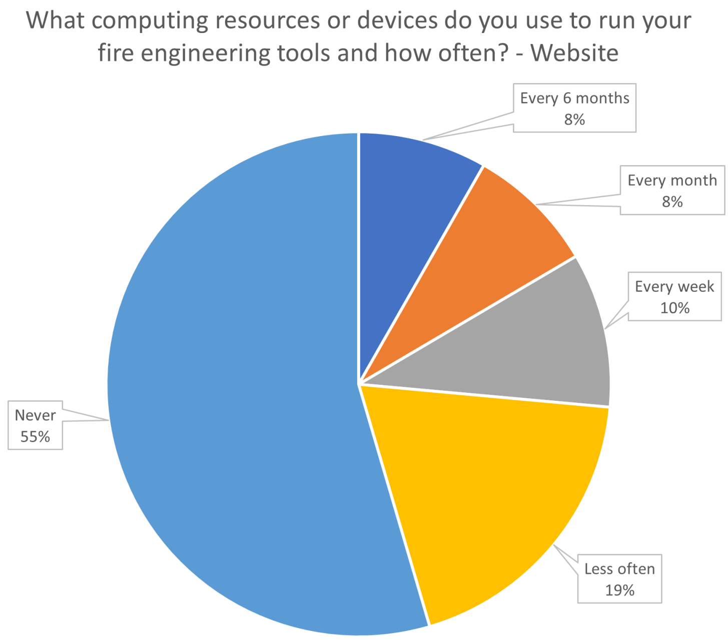

Figure 44. Frequency of use - websites.

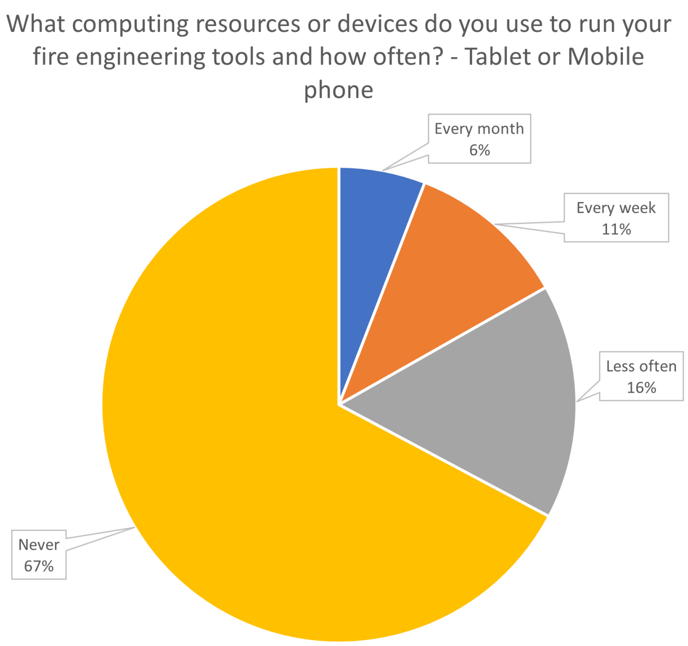

Figure 45. Frequency of use - tablet or mobile phone.

The survey respondents were then asked - *What computing resources or devices would you prefer to use in the future to run fire engineering tools?*. The results are presented in Figure 46 with the most common response being a local personal computer (32%) followed by cloud services (24%). Websites and mobile phones were the least popular choices.

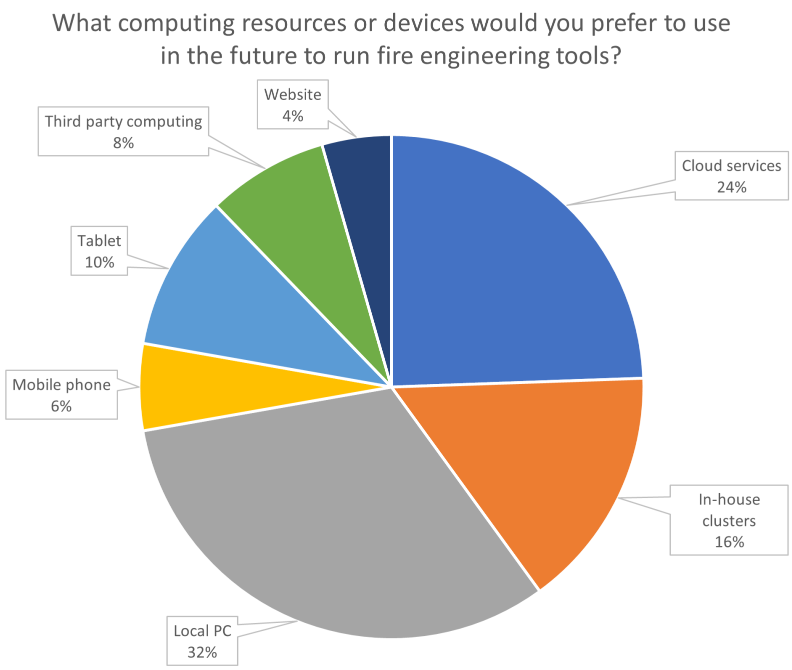

Figure 46. Preferred computing platform in the future.

5.4 Influence of the AHJ on tool selection

The survey respondents were asked - *Are you aware of any specific fire engineering tools required by the approving authority or regulator for projects that you or your company have completed?*. The results are presented in Figure 47 with 22% replying ”yes”. Detailed responses to this question are contained in Appendix B.

The most common specific tool requested by an Authority Having Jurisdiction (AHJ) was CFD analysis using FDS. There were some AHJ's requested CONTAM anaysis be provided for zoned smoke control or stair pressurisation design. In Portugal, the ARICA model is mentioned for existing buildings.

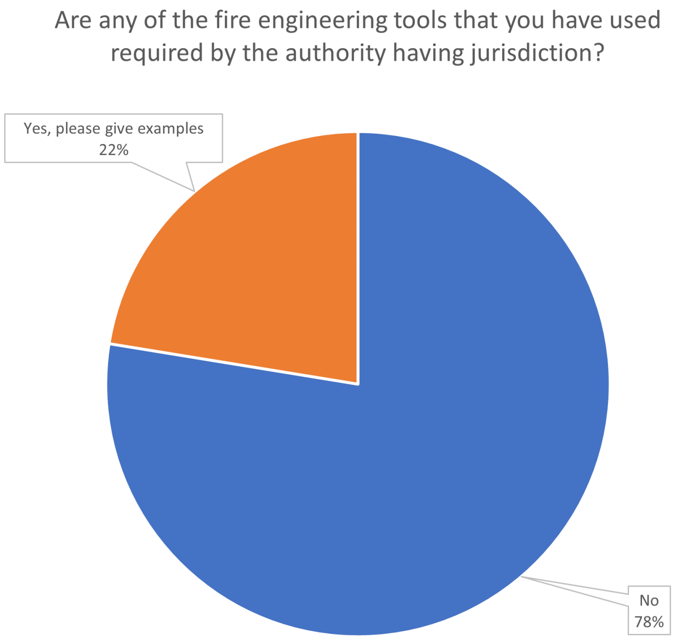

Figure 47. Tools required by the Authority Having Jurisdiction.

5.5 Current gaps and future needs

The survey respondents were asked - *Based on your knowledge and experience, what gaps exist in current fire engineering tools or what new tools should be developed?*

After reviewing all the individual responses, we decided to collate and group the responses to this question into eight general categories or themes, as follows:

1. Data
2. Documentation, guidance and education
3. Integration
4. New tools
5. Physics and conceptual models
6. Regulation
7. User experience
8. Validation

The detailed replies from the survey respondents are listed in Appendix C. Our analysis and discussion of the gaps and future needs identified in the survey is included in the following section 6.

5.6 Some additional comments

There was potential for some survey bias, based on the individuals who chose to respond not being truly representative of SFPE interests. For example there was almost no mention of fire practitioner needs in the wildland fire area and also relatively little generally mentioned that related to sustainability. This should be kept in mind when considering the survey results.

6. Analysis of Gaps and Future Needs

This section presents an overview and summary of the survey results with regard to identifying the gaps and future needs of fire engineering practitioners. The detailed replies are listed in Appendix C.

6.1 Summary of survey feedback

Survey responses were grouped into the general themes as listed in the previous subsection 5.5. These were: 1) data, 2) documentation, guidance and education, 3) integration, 4) new tools, 5) physics and conceptual model, 6) regulation, 7) user experience; and 8) validation.

In this section, within each of these themes, we highlight the various gaps and future needs from the survey replies.

6.1.1 Data

In the area of data, there was a general concern expressed regarding the availability of input data for use in models and calculations, with one respondent commenting - *"the greater challenge in the use of every tool is to find references for input data."* The quality of data was also a concern to some with another respondent commenting - *"the main gap is in the quality of the input data."*

Regarding the actual types of data mentioned, these included leakage data of building elements for smoke control design, as well as reliability data for fire protection equipment such as fire shutters, fire and smoke curtains.

Several respondents mentioned the need for more databases, for example *"comprehensive material property databases and MSDS information"* and *"an international database would be of great help for everyone in the fire community."*

The key gaps and needs can be summarised as:

GAPS - There is a lack of quality data for input to calculations and models.

NEEDS - Databases containing appropriate quality data are needed for use in calculations and models, particularly relating to reliability of fire protection systems, smoke leakage of building elements and material fire property data.

6.1.2 Documentation, guidance and education

Regarding the areas of documentation, guidance and education, a common theme was the need to provide more guidance on the proper application of models. One respondent stated - *"I think the knowledge gaps are more related to how the tools are applied"* and another said - *"adequate resources and awareness should be available regarding the importance of peer review and guidance on proper application of tools, particularly CFD fire modeling."* This also extended to the software documentation with another stating - *"any software should come with a detailed manual to explain not only how to use the tools, but background and general assumption."*

Quantitative risk assessment (QRA) received specific mention - *"there are plenty of validated tools for fire consequence modelling. What the sector lacks is an appreciation of the type of models needed to conduct a fire QRA for a building."*. This comment would be consistent with

Figure 17 where the use of inhouse methods and spreadsheets etc were the most common tool use for risk analysis.

Guidance on evaluating safety when making changes to existing buildings and to existing fire protection systems were also requested with replies such as - *"a guide is needed to support fire protection assessments for existing buildings"* and also *"a guide assisting fire protection professionals in the establishment of compensatory actions."*

The key gaps and needs can be summarised as:

GAPS - There is a lack of comprehensive guidance regarding the proper use and application of models; knowledge regarding suitable methods for QRA of buildings, and for evaluating safety in existing buildings.

NEEDS - Guidance is needed on the proper use and application of models; evaluating safety when making changes to existing buildings and fire protection systems; and in selecting appropriate methods for conducting QRA of building fire safety.

6.1.3 Integration

Within the general theme of integration, there was a very strong view that fire protection engineers were falling well behind the general architecture/engineering/construction industry with respect to the use of Building Information Management (BIM) tools. This is illustrated with specific comments such as - *"fire engineering, or fire safety documentation, should make its way into BIM (Building Information Modelling), where all the other design disciplines work and coordinate"* and *"the new tools needed are related to the evolution of Building Information Management ... further, the evolution in technology application in A/E is so removed from Fire, the fire industry risks being left behind."*

The reason for the low use of BIM tools by fire engineers seems to be due to the lack of fire-related BIM add-ins and the inability for many fire software applications to directly communicate with BIM tools like Revit. Typical comments were - *"The biggest gap is linking hydraulic calculations to Revit. Almost no sprinkler designers use Revit because there is no link."* and *"Revit tools for fire protection significantly lag behind the rest of the industry."*

There is also potential gains in efficiency by automatically extracting information from BIM/CAD tools illustrated by the comment - *"automatically generating models (various systems) from building plans would be helpful for many projects and in many different tools."*

Another aspect of integration that was dominant in the survey replies was that of coupling between models or software such as between fire and egress models. This is illustrated by comments such as - *"the ultimate would be the ability to model egress and fire development in the same model"* and *"a linked model which incorporates fire models and egress models together would be useful for more complex projects especially involving travel through smoke"* or *"refined interfaces linking egress and fire modelling with consequence assessments (FED/FIC etc)."*

The key gaps and needs can be summarised as:

GAPS - (1) There is a sizeable gap in the use of advanced building information models by the general design/engineering sectors in buildings compared with those used by fire engineers. (2) Not able to easily share data between tools.

NEEDS - (1) BIM/CAD tools/add-ins that provide input data for fire, egress, FEA and hydraulics models used by fire engineers. (2) There is also a need for better integration between different fire, egress, building response models used by fire engineers. This is a precursor to then being able to providing better QRA capabilities to fire engineers (e.g. Monte Carlo assessment of life safety consequence modelling).

6.1.4 New tools

There were many suggestions made by the survey respondents for where new tools might be developed. A common request was for a radiation calculator as illustrated by these replies - *"a tool that predicts the radiant heat transfer from multiple emitters onto a finite area receiver, with different orientations, such as acute/oblique angles, where 'traditional' view factors are not readily available "* and *"at present we mainly rely on in-house spreadsheets which use the view factors from the SFPE handbook, but sometimes these are insufficient, especially for more complex geometry, or for multiple radiating elements at angles other than parallel."*

There were also requests for simple spreadsheet-based tools to be developed such as -*"a new set of Excel spreadsheets for first cut calculations of fire phenomena"* and *"a single Excel suite/calculation software with various built-in tools for hand calculations of egress, structural assessments and QRA / risk visualizations. "* More specifically there is a need for both simpler as well as the more advanced tool with this reply in relation to egress calculations - *"simple building evacuation tool, generalised so that it is not geared to one national regulation system only, with control over parameters such as: flow capacities, route choice, realistic phased start of movement, stream merging."*

In the area of risk, there were several replies including - *"automated fire risk assessment methods should be a top priority as a new tool for building fire safety analysis"* and *"tools or parts of tools enabling risk informed analyses"*. A further extension of this would be including more probabilistic capability into models i.e *"systematic variation of input variables, entry as pdf of distributions of input"* and also for failure analysis - *"I haven't seen any software that is capable of cascading failure analysis."*

There were also a range of other suggestions made including: tools to evaluate firefighters response time and effectiveness; hydraulic calculators, flow of extinguishing gases; simple tools for estimating exterior fire propagation on facades; CLT/glulam structural fire engineering modelling software etc.

The key gaps and needs can be summarised as:

GAPS - There were various gaps based on the range of new tools mentioned.

NEEDS - Versatile/better radiation calculations; more standardised spreadsheets for simple egress or other calcs (eg parametric fire, burnout etc). Also desire for probabilistic models with QRA capabilities.

6.1.5 Physics and conceptual submodels

Within the general theme of improved physics and conceptual submodels, a commonly mentioned improvement here was in the area of modeling sprinkler spray interactions with the fire, with comments such as: *"we would benefit from a model that is capable of modelling sprinkler interactions with fires, especially with regard to reduced buoyancy in the plume"* and *"a proper way to model the fire development in a room with sprinklers."*

Improvements in pyrolysis, flame spread and fire growth submodels were mentioned by several of the survey respondents with comments such as *"models for pyrolysis of solids* *and evaporation of liquids need to be improved"* and *"If it were able to predict or calculate flame spread depending on e.g. material properties and had a better model for radiation, it would be unstoppable."*

There were various other responses that included better modelling of elevator use in egress calculations; further development of behavioural scenarios in agent based egress models; improved submodels for toxicology, soot deposition and calcination of gypsum board; timber charring; and also better quantification of dust suspension / entrainment in buildings and equipment, dust cloud combustion, ignition hazards, and deflagration effects.

The key gaps and needs can be summarised as:

GAPS - There were various gaps based on the range of suggested areas where modelling could be improved.

NEEDS - (1) Improvement and development of submodels to better address: Sprinkler spray interactions with the fire; (2) improved submodels for pyrolysis and charring, flame spread, toxicology, soot deposition, gypsum calcination; (3) improved submodels for elevator use and human behaviour in models; (4) Tools for combustible dust fire, flash fire, explosions and water delivery calculations.

6.1.6 Regulatory

In the area of regulation, there were a few replies seeking tools for checking code compliance e.g. *"a tool that looks across all codes and standards for a searched topic to help with determining the different requirements for a project in a jurisdiction"* but also tools targeting specific regulatory needs such as *"better tools for Eurocode 3"* or *"egress and burnout calcs to C/VM2"*.

There were also some concerns highlighting the need for more education of the AHJ such as - *"I believe the biggest issues are education of approval and referral authorities, so that they know what they are seeing and what they should be scrutinising."* as well as ensuring codes and regulations are evidence-based.

The key gaps and needs can be summarised as:

GAPS - Knowledge about appropriate use of models; lack of regulators adopting science- and evidence-based fire safety measures.

NEEDS - Automated code-checking tools; measure to guide/educate model users about appropriate use of models.

6.1.7 User experience

There were a number of survey replies concerned with the ease of use and general user experience in using various tools and software. There were requested for flexible editing of input with text based tools e.g. *"ability to use notepad or excel to edit HASS or Contam input/output as needed"*.

Regarding improving software front end interfaces, replies included - *"At present, I believe most platforms for analysis already exists. It's more a question of features and creating a better interface."* and *"A further improvement in front ends of the tools would make the tools more* *efficient and user friendly.".*

Also the presentation of outputs can be improved with one respondent commenting - *"representation of results is still relatively poor. We are constantly trying to improve it to communicate our results to our customers and improve explanation to authorities"* and another saying *"transition from spreadsheet-based tools to web-based / Python-based tools with nicer outputs."*

The key gaps and needs can be summarised as:

GAPS - Inefficient use of models and software due to time-consuming pre and post processing of input and output.

NEEDS - The main theme here is for easier to use software with improvements needed to existing user interfaces, and more useful presentation of outputs and results.

6.1.8 Validation

Finally, in the area of validation of models and software, the comments made were mainly concerned with improper use of software e.g. *"tools are often used far outside their field of validated application"* and *"many are based on empirical correlations that have long since been separated from their original statements of range of validity and application..."*

The key gaps and needs can be summarised as:

GAPS - Improper application of models and software.

NEEDS - More initiatives needed to avoid misuse of tools.

6.2 Gaps analysis and needs list

The identified gaps and future needs from subsection 6.1 are summarised in Table 1.

Table 1. List of gaps and future needs.

Theme	Gaps	Future Needs
1. Data	There is a lack of quality data for input to calculations and models.	Databases containing appropriate quality data are needed for use in calculations and models, particularly relating to reliability of fire protection systems, smoke leakage of building elements and material fire property data.
2. Documentation, guidance and education	There is a lack of comprehensive guidance regarding the proper use and application of models; knowledge regarding suitable methods for QRA of buildings, and for evaluating safety in existing buildings.	Guidance is needed on the proper use and application of models; evaluating safety when making changes to existing buildings and fire protection systems; and in selecting appropriate methods for conducting QRA of building fire safety.
3. Integration	There is a sizeable gap in the use of advanced building information models by the general design/engineering sectors in buildings compared with those used by fire engineers. Not able to easily share data between tools.	BIM/CAD tools/add-ins that provide input data for fire, egress, FEA and hydraulics models used by fire engineers. There is also a need for better integration between different fire, egress, building response models used by fire engineers. This is a precursor to then being able to providing better QRA capabilities to fire engineers (e.g. Monte Carlo assessment of life safety consequence modelling).
4. New tools	Various.	Versatile/better radiation calculations; more standardised spreadsheets for simple egress or other calcs (eg parametric fire, burnout etc). Also desire for probabilistic models with QRA capabilities.
5. Physics and conceptual models	Various.	Improvement and development of submodels to better address: Sprinkler spray interactions with the fire; Improved submodels for pyrolysis and charring, flame spread, toxicology, soot deposition, gypsum calcination; Improved submodels for elevator use and human behaviour in models; Tools for combustible dust fire, flash fire, explosions and water delivery calculations.
6. Regulation	Knowledge about appropriate use of models; lack of regulators adopting science- and evidence-based fire safety measures.	Automated code-checking tools; measure to guide/educate model users about appropriate use of models.
7. User experience	Inefficient use of models and software due to time-consuming pre and post processing of input and output.	The main theme here is for easier to use software with improvements needed to existing user interfaces, and more useful presentation of outputs and results.
8. Validation	Improper application of models and software.	More initiatives needed to avoid misuse of tools.

7. Listing of Commonly Used Tools

This section provides further information about some of the tools and software packages that were mentioned by the survey respondents as being tools that they use as previously shown in Figure 12.

7.1 Egress

7.1.1 General

A comprehensive review of egress model was published in 2010 by Kuligowski et al. [6]. Twenty-six models were categorised by their availability, overarching method of simulating occupants, purpose, type of grid/structure, perspective of the occupants, perspective of the building, internal algorithms for simulating occupant behaviour and movement, the incorporate of fire effects, the use of computer-aided design drawings, visualization methods, and validation techniques. The model listing compiled by Kuligowski et al. [6] is shown in Table 2.

Other special features were also noted such as whether they simulated phenomenon such as counterflow, exit blockages, fire conditions that affect behaviour, incapacitation of the occupants due to toxic smoke products, group behaviour, disabled or slower-moving occupant effects, pre-evacuation delays, elevator usage, and occupant route choice. The model listing showing these special features is shown in Table 3.

Kuligowski et al. [6] observed that in some cases, engineers were using back-of-the-envelope (hand) calculations to assess life safety, and in others, computational evacuation models are being used.

Lovreglio et al. [7] published results from an international online survey in 2020 regarding users' experiences of pedestrian evacuation models. Their survey consisted of 22 questions focusing on: the assessment of the pedestrian evacuation model user community; their stated importance of model features to select a model; usage/awareness of models; knowledge of model validation and verification; training; and usage of multiple models. Lovreglio et al. [7] concluded that verification and validation of the models was the most important factor affecting users' selection of a pedestrian evacuation model. They also identified 15 models as standing out since they were known by 10% of the 234 survey respondents from 41 countries.

Where hand calculations are made for mass flow evacuation from specified locations within a building, typically the equations given in the Society of Fire Protection Engineers (SFPE) Handbook or similar would be used in a spreadsheet. Kuligowski et al. [6] describe the base assumptions for these type of calculations as:

- The occupants are assumed to be standing at the doorway to the egress component on each floor as soon as the evacuation begins. [2]
- The calculation focuses mainly on points of constriction throughout the building (commonly the door to the outside, transitions between egress components, or where different paths merge together) and calculates the time for the occupants to move past these points and to the outside.

[2] The travel time to the door is usually ignored as this time is shorter than the queueing time.

Table 2. Main features of egress models (extracted from Ref [6])

Model	*Available to public*	*Modeling Method*	*Purpose*	*Grid/ Structure*	*Perspective of M/O*	*Behavior*[a]	*Movement*[a]	*Fire data*	*CAD*	*Visual*	*Valid*
EVACNET4	Y	M-O	1	C	G	N	UC	N	N	N	FD
WAYOUT	Y	M	5	C	G	N	D	N	N	2-D	FD
STEPS[c]	Y	B	1	F	I	C, P	P, E	Y1,2	Y	2,3-D	C,FD,PE
PEDROUTE	Y	PB	3	C	G	I	D	N	Y	2,3-D	N
Simulex[b]	Y	PB	1	Co.	I	I	ID	N	Y	2-D	FD,PE, 3P
GridFlow	Y	PB	1	Co.	I	I	D	N	Y	2,3-D	FD, PE
FDS+Evac[c]	Y	PB	1	Co.	I	I, C, P	ID	Y3	N/Y	2,3-D	FD,PE,OM
Pathfinder 2009[c]	Y	PB	1	Co.	I/G	I	D,ID	N	Y	2,3-D	C,FD,PE,OM
SimWalk[c]	Y	PB	1,3	Co.	I	C, P	P	N	Y	2,3-D	FD,PE,3P
PEDFLOW[c]	Y	B	1	Co.	I	C, P	ID	Y2	Y	2,3-D	PE
PedGo[c]	Y,N1	PB/B	1	F	I/I,G	I/C, P	P,E (CA), C	Y2	Y	2,3-D	FD,PE,OM,3P
ASERI[c]	Y	B-RA	1	Co.	I	C, P	ID	Y1,2	Y	2,3-D	FD, PE
BldEXO[b]	Y	B	1	F	I	C, P	P, E	Y1,2	Y	2,3-D	FD,PE,OM,3P
Legion[c]	Y,N1	B	1	Co.	I	AI, P	ID, C	Y1	Y	2,3-D	C,FD,PE,3P
SpaceSensor[c]	Y	B	3	Co.	I	C, P	C, Ac_K	N	Y	2,3-D	FD,OM
EPT[c]	Y,N1	B	1	F	I	AI	UC,C	Y2	Y	2,3-D	FD
Myriad II[c]	Y, N1	B	1	C, F, Co.	I	AI	D, UC, IP, Ac_K	Y1	Y	2,3-D	PE, 3P
MassMotion[c]	Y, N1	B	1	Co.	I/I,G	AI,P	C	N	Y	2,3-D	C,FD,PE,OM
PathFinder	N1	M	1	F	I/G	N	D	N	Y	2-D	N
ALLSAFE	N1	PB	5	C	G	I	Un_F	Y1,2	N	2-D	OM
CRISP	N1	B-RA	1	F	I	C, P	E,D	Y3	Y	2,3-D	FD
EGRESS 2002	N1	B	1	F	I	C, P	P,D (CA)	Y2	N	2-D	FD
SGEM[c]	N1	PB	1	Co.	I	I	D	N	Y	2-D	FD,OM
EXIT89[c]	N2	PB	1	C	I	I/C, P	D	Y1	N	N	FD,3P
MASSEgress[b]	N2	B	1	Co.	I	C, AI	C	N	Y	2,3-D	PE,OM
EvacuatioNZ[c]	N2	B	1	C	I/I,G	I, C, P	D, UC	Y2	Y	2-D	FD, PE,OM

[a]Only the underlying methods used by the algorithm are listed. In some instances users can define other options

[b]Model developers/NIST provided an update on the model's development in Spring 2009.

[c]Model developers/NIST provided an update on the model's development in Fall 2010.

Availability to the Public:
(Y): The model is available to the public for free or a fee
(N1): The company uses the model for the client on a consultancy basis
(N2): The model has not yet been released

Modeling Method:
(M): Movement model
(M-O): Movement/optimization models
(PB): Partial Behavioral model
(B): Behavioral model
(B-RA): Behavioral model with risk assessment capabilities

Purpose:
(1) Models that can simulate any type of building
(2) Models that specialize in residences
(3) Models that specialize in public transport stations
(4) Models that are capable of simulating low-rise buildings (under 15 stories)
(5) Models that only simulate 1-route/exit of the building.

Grid/Structure:
(C): Coarse network
(F): Fine network
(Co): Continuous

Perspective of the model/occupant:
(G): Global perspective
(I): Individual perspective
Each model is categorized by both the perspective of the model and of the occupant. If only one entry is listed in this column, both the model and occupant have the same perspective.

Behavior:
(N): No behavior
(I): Implicit
(C): Conditional or rule-based
(AI): Artificial intelligence
(P): Probabilistic

Movement:
(D): Density
(UC): User's choice
(ID): Inter-person distance
(P): Potential
(E): Emptiness of next grid cell
(C): Conditional
(Ac_K): Acquired knowledge
(Un_F): Unimpeded flow
(CA): Cellular automata

Fire Data:
(N): The model cannot incorporate fire data
(Y1): The model can import fire data from another model
(Y2): The model allows the user to input specific fire data at certain
(Y3): The model has its own simultaneous fire model

CAD:
(N): The model does not allow for importation of CAD drawings
(Y): The model does allow for importation of CAD drawings

Visual:
(N): The model does not have visualization capabilities
(2-D): 2-dimension visualization available
(3-D): 3-dimension visualization available

Validation:
(C): Validation against codes
(FD): Validation against fire drills or other people movement experiments/trials
(PE): Validation against literature on past experiments (flow rates, etc.)
(OM): Validation against other models
(3P): Third party validation
(N): No validation work could be found regarding the model

Table 3. Special features of egress models (extracted from Ref [6])

Model	*Counter-flow*	*Exit Block*	*Fire Conditions*	*Toxicity*	*Groups*	*Disabled / slower*	*Delays/pre-evacuation*	*Elevator use*	*Route choice*
EVACNET4	N	N	N	N	N	N	N	Y	Optimal routes
WAYOUT	N	N	N	N	N	N	Y	N	1 route, flows merge
STEPS[c]	Y	Y	Y	Y	Y	Y	Y	Y	Conditional
PEDROUTE	N	N	N	N	Y	Y	Y	N	Shortest, optimal, or signage
Simulex[b]	Y	Y	N	N	Y	Y	Y	N	Shortest or altered distance map
GridFlow	Y	Y	N	Y	N	Y	Y	N	Shortest, random, user-def.
FDS+Evac[c]	Y	Y	Y	Y	N	Y	Y	N	Optimal, conditional
Pathfinder 2009[c]	Y	Y	N	N	Y	Y	Y	N	Shortest, user-def.
SimWalk[c]	Y	N	N	N	Y	Y	Y	Y	Shortest
PEDFLOW[c]	Y	Y	Y	Y	Y	Y	Y	Y	Shortest, conditional
PedGo[c]	Y	Y	Y	N	Y	Y	Y	N	Probabilistic/conditional, user-def.
ASERI[c]	Y	Y	Y	Y	Y	Y	Y	N	Shortest, user-def., conditional
BldEXO[b]	Y	Y	Y	Y	Y	Y	Y	N	Various
Legion[c]	Y	Y	Y	Y	Y	Y	Y	Y	Conditional
SpaceSensor[c]	N	Y	N	N	N	N	N	Y	Conditional – visual perception
EPT[c]	Y	Y	Y	Y	Y	Y	Y	Y	Shortest, conditional
Myriad II[c]	Y	Y	Y	Y	Y	Y	Y	Y	Various
MassMotion[c]	Y	Y	Y	N	Y	Y	Y	Y	Shortest, conditional
PathFinder	N	N	N	N	N	N	N	N	User's choice – 2 choices
ALLSAFE	N	N	Y	N	Y	N	Y	N	1-Choice
CRISP	Y	Y	Y	Y	Y	Y	Y	N	Shortest, user-def., conditional
EGRESS 2002	Y	Y	Y	Y	Y	Y	Y	N	Conditional
SGEM[c]	Y	Y	N	N	N	Y	Y	Y	Shortest time, conditional
EXIT89[c]	Y	Y	Y	Y	N	Y	Y	N	Shortest distance, user-def.
MASSEgress[b]	Y	Y	N	N	Y	Y	Y	N	Conditional – visual perception
EvacuationNZ[c]	N	Y	Y	N	Y	Y	Y	N	Various

[b]Model developers/NIST provided an update on the model's development in Spring 2009.

[c]Model developers/NIST provided an update on the model's development in Fall 2010.

- These calculations treat the occupants as particles that follow known rules. Aside from density, interactions with other individuals, the building conditions (including fire effects), and the decision-making processes of the individuals are ignored.

A summary of the most common specific tools mentioned by the survey respondents are given in Table 4 with further information provided in the subsections below.

Table 4. Summary listing of most common models and tools used for egress.

Fire engineering tools for egress							
Model/Tool Name	Developed mainly for FSE	Description and Application	Features	Complexity	Supported?	Free?	User Interface
Pathfinder	YES	Agent based evacuation simulation model.	Uses a 3D triangulated mesh to represent the model geometry; support for the import of Autodesk formats DXF and DWG, buildingSMART's IFC format for BIM, as well as DWG, FBX, DAE, and OBJ.	HIGH	YES	NO	Windows OS.
Exodus	YES	Agent based evacuation simulation model.	Includes agent interaction with lifts, escalators and stairs, service queues, exit usage according to occupant familiarity, agent interaction with signage, and group dynamics.	HIGH	YES	NO	Windows OS.
FDS+Evac	YES	An evacuation simulation module for FDS.	The evacuation simulations can be fully coupled with the fire simulations.	HIGH	YES	YES	Windows OS.
Steps	NO	A pedestrian microsimulation tool that helps integrate pedestrian movements within infrastructure plans.	A fine network model.	HIGH	YES	NO	Windows OS.
Simulex		Simulates how occupants move around a building day-to-day and evacuate during an emergency.	The building is represented by a plane for each floor, and planes can be connected with stairs. The agents in the program move on the plane and reduce their speed as a function of the distance to others and building features.	HIGH	YES	NO	Windows OS.

7.1.2 Pathfinder

Pathfinder is an agent based evacuation simulation model [11] developed by Thunderhead Engineering. It is used internationally by engineering consultants and academic institutions.

Pathfinder provides support for the import of Autodesk formats DXF and DWG, buildingSMART's IFC format for BIM, as well as DWG, FBX, DAE, and OBJ. It uses a 3D triangulated mesh to represent the model geometry. Pathfinder supports two simulation modes. In Steering mode, agents proceed independently to their goal, while avoiding other occupants and obstacles. Door flow rates are not specified but result from the interaction of occupants with each other and with boundaries. In SFPE mode, agents use behaviours that follow SFPE guidelines, with density-dependent walking speeds and flow limits to doors. By default, each occupant (agent) uses a combination of parameters to select their current path to an exit. The parameters include: queue times for each door of the current room, the time to travel to each door of the current room, the estimated time from each door to the exit, and the distance already traveled in the room.

Pathfinder is available for a fee with further information at:
https://www.thunderheadeng.com/pathfinder/

7.1.3 Exodus

EXODUS can be used for both evacuation simulation and pedestrian dynamics/circulation analysis [12] and is developed at the University of Greenwich, UK. EXODUS comprises a suite of software packages, tailored to the building, maritime, rail and aircraft environments. EXODUS can simulate the interaction of many thousands of people with ability to represent agent interaction with lifts, escalators and stairs, service queues, exit usage according to occupant familiarity, agent interaction with signage, and group dynamics.

EXODUS is available for a fee with further information at:
https://fseg.gre.ac.uk/exodus/

7.1.4 FDS+Evac

FDS+Evac [13] is an evacuation simulation module for Fire Dynamics Simulator (FDS) developed and maintained by VTT in Finland. The software is used to simulate the movement of people in evacuation situations. The evacuation simulations can be fully coupled with the fire simulations. FDS+Evac treats each evacuee as a separate entity, or an 'agent', which has its own personal properties and escape strategies. The movement of the agents is simulated using two-dimensional planes representing the floors of buildings. The evacuation module is embedded inside FDS. Thus, the running of FDS+Evac evacuation simulation is effectively very similar to running an ordinary FDS fire simulation.

FDS+Evac is available for free with further information at:
http://virtual.vtt.fi/virtual/proj6/fdsevac/documents/FDS+Evac_textbased_homepage.txt

7.1.5 STEPS

STEPS [14], or Simulation of Transient Evacuation and Pedestrian movements Software, is a pedestrian microsimulation tool that helps integrate pedestrian movements within infrastructure plans. It was developed at Mott MacDonald. The building is represented by a grid in STEPS, and each grid cell can only hold one person, i.e., STEPS is an example of a fine network model. A grid can represent a floor (or part of flow), ramps or even stairs. Movement through openings needs to be restricted in STEPS in order to get realistic flows through exits.

STEPS is available for a fee with further information at:
https://www.steps.mottmac.com/steps-dynamics

7.1.6 Simulex

Simulex [15] enables a building to be defined, and simulates how occupants move around a building day-to-day and evacuate during an emergency. The building is represented by a plane for each floor, and planes can be connected with stairs. The agents in the program move on the plane and reduce their speed as a function of the distance to others and building features. Simulex is an example of a continuous evacuation model. Can use VE or CAD generated DXF files to create and define each floor plan.

Simulex is available for a fee from Integrated Environmental Solutions Limited with further information at:
https://www.iesve.com/software/virtual-environment/applications/egress/simulex.

7.2 Fire and/or smoke development and spread

7.2.1 General

In 1992 an international survey of fire models for fire and smoke by Raymond Friedman was published in the SFPE Journal of Fire Protection Engineering [1]. This survey listed 62 models divided into various categories (e.g. zone models, field models, evacuation models etc.). Very few of these models are in current use today. The survey was updated in

2003 by Olenick and Carpenter [2] and again published in the SFPE Journal of Fire Protection Engineering. Further updates were conducted in 2007, 2010, and 2013/2014 by Combustion Science and Engineering with the most recent results included on a website (http://firemodelsurvey.com/index.html). Models were identified as either actively supported or archived.

A summary of the most common specific tools mentioned by the survey respondents are given in Table 5 with further information provided in the subsections below.

7.2.2 FDS

Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) model of fire-driven fluid flow developed at NIST [16]. The software solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires.

FDS is available for free with further information at:
https://github.com/firemodels/fds/wiki/FDS-Road-Map and https://github.com/firemodels/fds.

7.2.3 OpenFoam

OpenFoam [17] is open source computional fluid dynamics software. It includes combustion capability and a transient solver for fires and turbulent diffusion flames with reacting particle clouds, surface film and pyrolysis modelling.

OpenFoam is available for free with further information at:
https://cfd.direct/openfoam/.

FireFOAM is an LES solver based on OpenFOAM, which is FM Global's selected Open Source CFD Toolbox and platform for fire and explosion modeling applications.

Further information about FireFoam is found at:
https://www.fmglobal.mobi/research-and-resources/research-and-testing/theoretical-computational-a
open-source-fire-modeling.

7.2.4 CFAST

CFAST [18, 19] is a two-zone fire model developed at NIST capable of predicting the environment in a multi-compartment structure subjected to a fire. It calculates the time-evolving distribution of smoke and gaseous combustion products as well as the temperature throughout a building during a user-prescribed fire.

NIST have also recently developed a CFAST Fire Data Generator (CData) [20] providing a means of providing Monte Carlo capability for CFAST simulations. CData makes use of the statistical software, R, for selected analyses of the data generated for multiple CFAST runs. CData is installed as part of the CFAST distribution.

CFAST is available for free with further information at:
https://pages.nist.gov/cfast/index.html.

Table 5. Summary listing of most common models and tools used for fire and/or smoke development and spread.

Fire engineering tools for fire and/or smoke development and spread							
Model/Tool Name	Developed mainly for FSE	Description and Application	Features	Complexity	Supported?	Free?	User Interface
FDS	YES	CFD fire model of fire-driven fluid flow	Hydrodyamic and combustion models; radiation heat transfer; approximates the governing equations on a rectilinear grid; multiple meshes; parallel processing.	HIGH	YES	YES	64 bit Windows, Linux, or Mac OS X operating system. Run from command line from text input files, Relies on 3rd party apps for user interface.
CFAST	YES	Zone fire model for simulating fire and smoke spread	CFAST Fire Data Generator (CData) provides a means of providing Monte Carlo capability for CFAST simulations.	MED	YES	YES	Windows OS. Moderately easy to use.
B-RISK	YES	Zone fire model for simulating fire and smoke spread	Includes a wide range of submodels. Includes some Monte Carlo capability allowing selected input to be sampled from a set of defined statistical distributions.	MED	YES	YES	Windows OS. Moderately easy to use.
FireWind	YES	package of 18 programs covering different aspects of fire technology and fire protection science.	One-room and two-rooms zone models; sprinkler activation calculations combined with a zone model; model of evacuation from a multi-room and multi-storey building; and heat radiation calculations (most commonly mentioned by users).	LOW	YES	NO	Windows OS. Simple, easy to use interface.
TRA	YES	For thermal radiation calculations normally associated with fire engineering design including fire spread between buildings and egress via evacuation routes.	Includes fire spread between buildings and egress via evacuation routes. It may also be used to verify configuration factors used within heat transfer calculations.	LOW	YES	NO	Windows OS. Simple, easy to use interface.
OZONE	YES	Calculation of heat transfer to steel elements with a fire zone model included	Two-zone and a single-zone model. Calculation of the gas temperature in case of fire according to EN 1991-1-2 and corresponding steel temperature according to EN 1993-1-2.	MED	UNKNOWN	YES	Windows OS. Simple, easy to use interface.
CONTAM	YES	Multizone indoor air quality and ventilation analysis includng smoke control systems.	Calculates building airflow rates and relative pressures between zones of a building. Has also been used extensively for the design and analysis of smoke management systems.	MED	YES	YES	Graphical user interface (referred to herein as ContamW) for Windows OS.
ANSYS Fluent	No	CFD fire model of fluid flows.	It includes various physics models such as turbulence modeling, combustion and conjugate heat transfer.	HIGH	YES	NO	Pro version tailors the user-friendly interface for less complex CFD simulations by reducing the physics capabilities exposed to the user.
Vultijdenmodel	YES	Smoke filling model from the Netherlands.	Design aid for smoke exhaust systems (NEN 6093).	MED	YES	NO	Windows OS. Simple, easy to use interface.
StarCCM+	NO	CFD fire model of fluid flows.	It allows modeling and analysis of a range of engineering problems involving fluid flow, heat transfer, stress, particulate flow, etc.	HIGH	YES	NO	Windows OS. Can be used from any public/private cluster, network or cloud.
OpenFoam	NO	CFD fire model of fluid flows. Open source.	Includes FireFoam as combustion solver.	HIGH	YES	YES	Requires a third party user interface.

7.2.5 B-RISK

B-RISK [21] is a two-zone fire model developed at BRANZ capable of predicting the environment in a multi-compartment structure subjected to a fire. It calculates the time-evolving distribution of smoke and gaseous combustion products as well as the temperature throughout a building during a user-prescribed fire. B-RISK include a range of optional submodels including glass fracture, spill plumes, sprinkler and detector actuation, postflashover fire, flame spread and heat release from combustible linings and item to item fire spread using a ”design fire generator”. It also includes some Monte Carlo capability allowing selected inputs to be sampled from a set of defined statistical distributions.

B-RISK is available for free with further information at:
https://www.branz.co.nz/fire-safety-design/b-risk/.

7.2.6 OZONE

OZONE [22] is a model to aid the design of structural elements submitted to compartment fires that includes a single compartment fire model. The model includes a two-zone and a single-zone model with the ability to switch from the two-zone to the one-zone model based on specified criteria. It therefore deals with localised and fully developed fires. The wall model is based on the finite element method and is fully coupled to the zone equations.

Calculation of the gas temperature in case of fire according to EN 1991-1-2 and corresponding steel temperature according to EN 1993-1-2.

OZONE is available for free with further information at:
https://sections.arcelormittal.com/design_aid/design_software/EN.

7.2.7 CONTAM

CONTAM [23] is a computer program for multizone indoor air quality and ventilation analysis including smoke control systems developed by NIST, designed to help determine:

- airflows: infiltration, exfiltration, and room-to-room airflows in building systems driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by the indoor and outdoor air temperature difference.
- contaminant concentrations: the dispersal of airborne contaminants transported by these airflows; transformed by a variety of processes including chemical and radio-chemical transformation, adsorption and desorption to building materials, filtration, and deposition to building surfaces, etc.; and generated by a variety of source mechanisms, and/or
- personal exposure: the predictions of exposure of occupants to airborne contaminants for eventual risk assessment.

CONTAM is available for free with further information at:
https://www.nist.gov/services-resources/software/contam.

7.2.8 ANSYS Fluent

ANSYS Fluent is commercial computational fluid dynamics simulation software with a user-firendly interface and parallel capabilities for meshing and solving. It includes various physics models such as turbulence modeling, combustion and conjugate heat transfer.

ANSYS Fluent is available for a fee with further information at: https://www.ansys.com/products/fluids/ansys-fluent.

7.2.9 MZ Fire Model

The Multi-Zone (MZ) fire zone model [24, 25] can be used to calculate the consequences of fire in wider range of enclosure volumes (compared to a one or two zone model) and provides an intermediate level of resolution that falls between a two-zone and a CFD model. The MZ fire model provides the possibility to model the influence of: multiple time dependent fires; vertical and horizontal vents in the enclosure boundaries; and internal obstacles like walls. The model uses a text-based input file and it is available for download online. Johansson evaluated the model and found that it over predicted the temperatures under the ceiling by 30–40 °C, corresponding to around 10–15% of the measured gas temperature.

MZ Fire Model is available for free with further information at: https://mzfiremodel.com/.

7.2.10 Thermal Radiation Analysis (TRA)

Thermal Radiation Analysis is designed to analyse complex or simple thermal radiation problems normally associated with fire engineering design including fire spread between buildings and egress via evacuation routes. It may also be used to verify configuration factors used within heat transfer calculations.

TRA is available for a fee with further information at:

http://www.fire-engineering-software.com/tra.html.

7.2.11 FireWind

Computer software package of 18 programs covering different aspects of fire technology and fire protection science. It includes: one-room and two-rooms zone models which take into account various ventilation conditions; sprinkler activation calculations combined with a zone model; model of evacuation from a multi-room and multi-storey building; and heat radiation calculations.

FireWind is available for a fee with further information at: http://members.optusnet.com.au/~firecomp/.

7.2.12 Vultijdenmodel

Vultijdenmodel is a smoke-filling model developed in the Netherlands. It can also be used in the design of smoke exhaust systems (NEN 6093).

Vultijdenmodel is available for a fee with further information at: http://www.peutzdata.nl/node/7.

7.2.13 STAR-CCM+

STAR-CCM+ is a commercial CFD program developed by Siemens Digital Industries Software. It allows modeling and analysis of a range of engineering problems involving fluid flow, heat transfer, stress, particulate flow, etc. It has a single integrated environment that includes CAD, automated meshing, multiphysics CFD and sophisticated postprocessing. It can also be purchased using on demand per hour licensing usable from any public/private cluster, network or cloud.

STAR-CCM+ is available for a fee with further information at: https://www.plm.automation.siemens.com/global/en/products/simcenter/STAR-CCM.html.

7.3 Response to elevated temperatures

A summary of the most common specific tools mentioned by the survey respondents are given in Table 6 with further information provided in the subsections below.

Table 6. Summary listing of most common models and tools used for response to elevated temperatures.

Fire engineering tools for response to elevated temperatures							
Model/Tool Name	Developed mainly for FSE	Description and Application	Features	Complexity	Supported?	Free?	User Interface
SAFIR	YES	Nonlinear finite element software for modeling the behavior of building structures subjected to fire.	Different materials such as steel, concrete, timber, aluminum, gypsum or thermally insulating products can be used separately or in combination in the model. Calculates the evolution of the temperature in the structural elements which can be discretized in 2D or 3D.	MED	YES	NO	Windows OS.
TASEF	YES	Finite element computer program for the analysis of temperature distribution in sections which are exposed to fire or other sources of high temperatures.	Handles plane or axi-symmetric cross-sections. 2D analysis. Cut outs and voids can be incorporated in the section geometry.	MED	YES	NO	Windows OS. Properties of steel and concrete based on Eurocodes 2-4 are built into the input generator TASEFplus.
ABAQUS	NO	Abaqus FEA is a software suite for finite element analysis and computer-aided engineering.	It has a wide range of non-linear analysis procedures including structural stress, explicit dynamics, thermal stress, heat transfer, pore fluid diffusion, and more.	HIGH	YES	NO	Windows OS.

7.3.1 SAFIR

SAFIR is nonlinear finite element software for modeling the behaviour of building structures subjected to fire [26]. The structure can be made of a 3D skeleton of linear elements such as beams and columns, in conjunction with planar elements such as slabs and walls. Volumetric elements can be used for analysis of details in the structure such as connections. Different materials such as steel, concrete, timber, aluminum, gypsum or thermally insulating products can be used separately or in combination in the model.

SAFIR is available for a fee with further information at: https://www.gesval.be/en/catalogue/safir-2019-commercial.

7.3.2 TASEF

TASEF is a finite element computer program for the analysis of temperature distribution in sections which are exposed to fire or other sources of high temperatures. TASEF handles plane or axi-symmetric cross-sections. TASEF uses the finite element method for thermal analysis in two dimensions. Thermal material properties like conductivity and specific volumetric enthalpy (density and specific heat capacity) can vary with temperature and latent heat due to water evaporation can be modelled. Properties of steel and concrete based on Eurocodes 2-4 are built into the input generator TASEFplus. Completely customised material properties can also be defined. The meshing of the cross-section is shown by a graphical interface. Cut outs and voids can be incorporated in the section geometry [27].

TASEF is available for a fee with further information at:
http://www.tasefplus.com/index.html.

7.3.3 ABAQUS

Abaqus FEA is a software suite for finite element analysis and computer-aided engineering. It has a wide range of non-linear analysis procedures including structural stress, explicit dynamics, thermal stress, heat transfer, pore fluid diffusion, and more.

ABAQUS is available for a fee with further information at:
https://www.3ds.com/products-services/simulia/products/abaqus/.

7.4 Hydraulic flows, suppression and detection system design

A summary of the most common specific tools mentioned by the survey respondents are given in Table 7 with further information provided in the subsections below.

7.4.1 HASS

Hydraulic Analyzer of Sprinkler Systems (HASS) is software from HRS Systems, Inc. for analysing the hydraulic design of sprinkler systems. It enables hydraulic calculations to determine water supply adequacy based on system demand and distribution piping in accordance with NFPA 13, 13D, 13R, 14, 15, 20, 24, 750 and other standards, calculating any connection of nodes and pipes. It can also be used for water mist systems, foam concentrate and other liquids.

HASS is available for a fee with further information at:
https://www.hrssystems.com/hass.

7.4.2 HydraCALC

HydraCALC is software handling the fundamental principles of pressure loss calculations and water flow through a sprinkler head and other types of nozzles. There is also a version of HydraCALC for Revit that will produce hydraulic calculations directly from standard Revit drawings. This software can use the families that ship with Revit, with a few user-initiated changes.

HydraCALC is available for a fee with further information at:
https://www.hydratecinc.com/hydratec-software#HCALC.

Table 7. Summary listing of most common models and tools used for hydraulic flows, suppression and detection system design.

Fire engineering tools for hydraulic flows, suppression and detection system design							
Model/Tool Name	Developed mainly for FSE	Description and Application	Features	Complexity	Supported?	Free?	User Interface
HASS	YES	For the hydraulic design of sprinkler systems. Determines water supply adequacy based on system demand and distribution piping.	With HASS, you can perform hydraulic analysis in accordance with NFPA 13, 13D, 13R, 14, 15, 20, 24, 750 and other standards, calculating any connection of nodes and pipes. Also for water mist systems (NFPA 750), foam concentrate and other liquids.	MED	YES	NO	Windows OS.
HydraCALC	No	Hydraulic calculation software.	A job designed in HydraCAD can be analyzed with Hydraulics; Library of pump and backflow device curves included. Calculates using Velocity Pressure or Total Pressure. Calculates using Hazen-Williams or Darcy-Weisbach. Integrates with HydraCAD™.	MED	YES	NO	Windows OS. Full screen graphics display. Many predefined submittal printout forms.
DETACT	YES	For calculating the actuation time of thermal devices below unconfined ceilings.	This is archival software and no longer supported.	LOW	NO	YES	Runs from command line in 32-bit Windows OS.
FPETool	YES	Includes a set of engineering equations useful in estimating potential fire hazard and the response of the space and fire protection systems to the developing hazard. Current use of FPEtool appeared to be primarily for calculation of response time of sprinklers and detectors.	This is archival software and no longer supported.	MED	NO	YES	Runs from command line in 32-bit Windows OS.
Hyena	YES	Hydraulic calculation software.	The program can be used to carry out a sprinkler system analysis in accordance with NFPA, NZ4541, AS2118 or SSPC52 or to carry out an analysis of hydrant systems with or without hoses or hose reels.	MED	YES	NO	Windows OS. Input data is via a series of screens with numerous features including drop down lists, selection lists, various sort options, etc; to facilitate easy data input.
Elite Software Fire program	YES	Hydraulic calculation software for sprinklers.	hydraulic calculations as required by NFPA 13. Flows are calculated using the Hazen Williams equation.	MED	YES	NO	Windows OS. Various reports included.
AutoSPRINK	YES	Hydraulic calculation software for sprinklers.	Combined CAD and hydraulic calculation software for designing sprinkler systems in 3D.	MED	YES	NO	Windows OS.

7.4.3 DETACT

DETACT-QS (DETector ACTuation - Quasi Steady) is a program for calculating the actuation time of thermal devices below unconfined ceilings. It can be used to predict the actuation time of fixed temperature heat detectors and sprinkler heads subject to a user specified fire.

This is archival software, difficult to use on modern operating systems and no longer supported. DETACT is available for free with further information at:
https://www.nist.gov/el/fire-research-division-73300/fire-modeling-programs.

7.4.4 FPETool

FPETool is a program developed by NIST including a set of engineering equations useful in estimating potential fire hazard and the response of the space and fire protection systems to the developing hazard. Version 3.2 incorporates an estimate of smoke conditions developing within a room receiving steady-state smoke leakage from an adjacent space. Estimates of human viability resulting from exposure to developing conditions within the room are calculated based upon the smoke temperature and toxicity. Current use of FPEtool appeared to be primarily for calculation of response time of sprinklers and detectors.

This is archival software, difficult to use on modern operating systems and no longer supported. FPETool is available for free with further information at:
https://www.nist.gov/el/fire-research-division-73300/fire-modeling-programs.

7.4.5 Hyena

Hydraulic Analysis of Fire Sprinkler and Hydrant Systems (Hyena) developed by ACADS–BSG in Australia can be used to analyse automatic fire sprinkler systems with a simple end, side or centre fed configuration or more complicated looped and gridded systems. It may also be used to analyse fire hydrant and hose reel installations or combined sprinkler, hydrant and/or hose reel systems or any other systems where the discharges can be represented by a k factor and minimum flow. With a given sized network the program performs a complete hydraulic analysis determining the water flow in, and pressure drop though, each pipe in the entered network taking account of all fittings entered by the user.

The program operates under Windows OS and all input data is via a series of screens with numerous features including drop down lists, selection lists, various sort options, etc; to facilitate easy data input. The program can be used to carry out a sprinkler system analysis in accordance with NFPA, NZS4541, AS2118 or SSPC52 or to carry out an analysis of hydrant systems with or without hoses or hose reels.

Hyena is available for a fee with further information at:
https://www.acadsbsg.com.au/hyena/.

7.4.6 Elite Software Fire

Elite Software Fire performs all necessary hydraulic calculations as required by NFPA 13. It estimates sprinkler head requirements, calculates optimal pipe sizes, and automatically performs a peaking analysis. Fire can handle all types of sprinkler systems (trees, grids, loops, and hybrids) with up to 1,000 or more sprinklers and pipes. Meters, backflow preventers, alarm check valves and standpipes can also be analysed. It uses the Newton Raphson matrix solution technique to solve pipe networks, and each pipe is defined to flow according to the Hazen Williams equation.

Elite Software Fire is available for a fee with further information at:
https://www.elitesoft.com/web/fire/elite_fire_info.html.

7.4.7 AutoSprink

AutoSPRINK is combined CAD and hydraulic calculation software for designing sprinkler systems in 3D.

AutoSprink is available for a fee with further information at:
https://autosprink.com/.

7.5 Data processing and visualisation

A summary of the most common specific tools mentioned by the survey respondents are given in Table 8 with further information provided in the subsections below.

Table 8. Summary listing of most common models and tools used for data processing and visualisation.

Fire engineering tools for data processing and visualisation							
Model/Tool Name	Developed mainly for FSE	Description and Application	Features	Complexity	Supported?	Free?	User Interface
Pyrosim	YES	Software for working with FDS models.	It allows IFC, DXF, DWG, FBX, STL, and FDS files produced by external sources to be imported and thereby reduces the amount of time spent recreating the architectural geometry for FDS models. PyroSim allows interactive editing of properties associated with all objects in a model. It also allows smoke, temperature, velocity, toxicity, and other outputs of the FDS analysis to be viewed and videos to be created in real-time.	MED	YES	NO	
SmokeView	YES	A visualization program that is used to display the results of an FDS simulation. Can also be used with CFAST and B-RISK (latter requires older version of SmokeView).	Includes algorithms for for visualizing 3D smoke. Smokeview presently visualizes smoke by over-laying partially transparent planes. The smoke opacities in each plane are computed using the Beer-Lambert law, using soot propagation data computed by	MED	YES	YES	64 bit Windows, Linux, or Mac OS X operating system.
Blender FDS	YES	Blender FDS is the graphic interface for FDS.	BlenderFDS helps build complex FDS models faster with 3D editing tools. Can import CAD models and existing FDS input files.	MED	YES	YES	BlenderFDS is available for MS Windows, MacOSX, Linux. Open source.

7.5.1 Smokeview

Smokeview (SMV) is a visualization program that is used to display the output of FDS and CFAST simulations. Smokeview presently visualizes smoke by over-laying partially transparent planes. The smoke opacities in each plane are computed using the Beer-Lambert law, using soot propagation data computed by FDS.

Smokeview is available for free with further information at: https://github.com/firemodels/fds/wiki/Smokeview-Road-Map.

7.5.2 PyroSim

PyroSim is software for working with FDS models. It allows IFC, DXF, DWG, FBX, STL, and FDS files produced by external sources to be imported and thereby reduces the amount of time spent recreating the architectural geometry for FDS models. PyroSim allows interactive editing of properties associated with all objects in a model. It also allows smoke, temperature, velocity, toxicity, and other outputs of the FDS analysis to be viewed and videos to be created in real-time.

PyroSim is available for a fee with further information at: https://www.thunderheadeng.com/pyrosim/.

7.5.3 Blender FDS

Blender FDS is a graphic interface for FDS developed by CFD FEA Service in Italy and which allows the user to create simulation input files for FDS. Can import CAD models and existing FDS input files. BlenderFDS is developed in Python and is open source.

Blender FDS is available for a fee with further information at:
https://cfdfeaservice.it/index.php/prodotto/blender-fds/.

7.6 Information management, CAD, BIM

7.6.1 General

There is increasing interest in the use of Building Information Models to record and preserve information about buildings over their life cycle. However Galea et al. [28] have noted a number of challenges that contribute to lack of use of BIM by the fire engineering community. These challenges include: no FSE specific information exchange is available in BIM and that the results produced by fire and evacuation modelling tools are not explicitly captured in the BIM Industry Foundation Classes (IFC) Model.

A summary of the most common specific tools mentioned by the survey respondents are given in Table 9 with further information provided in the subsections below.

Table 9. Summary listing of most common models and tools used for information management, CAD, BIM.

Fire engineering tools for information management, CAD, BIM							
Model/Tool Name	Developed mainly for FSE	Description and Application	Features	Complexity	Supported?	Free?	User Interface
AutoCAD	NO	Computer-aid design software for building geometry, floor plans etc.	Part of the Autodesk Architecture, Engineering & Construction Collection that provides designers, engineers and contractors with BIM and CAD tools.	HIGH	YES	NO	Windows OS.
Revit	NO	BIM software	Part of the Autodesk Architecture, Engineering & Construction Collection that provides designers, engineers and contractors with BIM and CAD tools.	HIGH	YES	NO	Windows OS.
Navisworks	NO	Project review software to improve BIM co-ordination.	Part of the Autodesk Architecture, Engineering & Construction Collection that provides designers, engineers and contractors with BIM and CAD tools.	HIGH	YES	NO	Windows OS.
BlueBeam Revu	NO	PDF-based collaborative commenting, markup and measurement tool.	Allows teams to review, markup and update the same files at the same time or manage and share documents online.	MED	YES	NO	Windows OS.
SolidWorks	NO	3D design CAD software	Includes 3D models and 2D drawings of complex parts and assemblies.	HIGH	YES	NO	Windows OS.

7.6.2 Revit

Revit is BIM software that allows architecture, engineering and construction disciplines to share a unified modelling environment. It is part of the Autodesk Architecture, Engineering & Construction Collection that provides designers, engineers and contractors with BIM and CAD tools.

Revit is available for a fee with further information at:
https://www.autodesk.co.nz/products/revit/overview?term=1-YEAR.

7.6.3 Navisworks

Navisworks is project review software to improve BIM (Building Information Modelling) co-ordination. It is part of the Autodesk Architecture, Engineering & Construction Collection that provides designers, engineers and contractors with BIM and CAD tools.

Navisworks is available for a fee with further information at:
https://www.autodesk.com/products/navisworks/features.

7.6.4 AutoCAD

AutoCAD is computer-aided design (CAD) software that architects, engineers, and construction professionals can use to create precise 2D and 3D drawings. It is part of the Autodesk Architecture, Engineering & Construction Collection that provides designers, engineers and contractors with BIM and CAD tools.

AutoCAD is available for a fee with further information at:
https://www.autodesk.com/products/autocad/overview?term=1-YEAR.

7.6.5 BlueBeam Revu

BlueBeam Revu is a PDF-based collaborative commenting, markup and measurement tool. It also allows teams to review, markup and update the same files at the same time or manage and share documents online.

BlueBeam is available for a fee with further information at:
https://www.bluebeam.com/solutions/engineer.

7.6.6 SolidWorks

SolidWorks is 3D design CAD software, including 3D models and 2D drawings of complex parts and assemblies.

SolidWorks is available for a fee with further information at:
https://www.solidworks.com/domain/design-engineering.

7.7 Other

7.7.1 @RISK

@RISK is an add-in to Microsoft Excel from Palisade Software for analysing uncertainty and risk problems using Monte Carlo simulation. It includes a broad library of probability distributions, data fitting tools, and correlation modeling.

@RISK is available for a fee with further information at:
https://www.palisade.com/risk/.

7.7.2 ARICA Method

The ARICA Method [29] is used in Portugal for assessing fire risk in old urban areas and is based, initially, on the determination of four risk factors. The risk factors are: 1) global risk factor associated with the onset of fire, 2) global risk factor associated with the development and spread of fire in the building, and 3) a global risk factor associated with evacuation of the building and 4) a global factor associated with firefighting. ARICA is a points based method amenable to a spreadsheet.

7.7.3 FBIM

FBIM [30] has been developed to determine the time required to allow for the following fire brigade tasks: notification, dispatch, response, arrival, access, information and assessment, strategy determination, set up, search and rescue, exposure protection, environmental protection, fire control and extinguishment. FBIM complements the performance based regulatory framework of Australia and New Zealand. The FBIM 2006 software version is designed to run on the 32-bit versions of Windows XP, Windows 7 Home Edition or Windows 7 Professional.

FBIM is available for a fee with further information at:
https://www.afac.com.au/auxiliary/shop/product-category?ID=26.

8. Future Work Plan

This chapter of the report provides recommendations from the authors as to a future work plan for both the Foundation and the SFPE. These recommendations have been informed by the data that have been gathered during the course of the present project, primarily the gaps and future needs identified by fire engineering tools survey respondents, and which are summarised in Table 1. The contents of this chapter are structured in a similar manner to the themes listed in Table 1.

The SFPE Research Roadmap (https://www.sfpe.org/research/research-roadmap) is also referred to as a basis for prioritizing the different elements of the future work plan recommendations. The SFPE Roadmap is reproduced in Appendix D.

As noted in subsection 4.2 of this report, 156 individuals responded to this survey and the analysis that is presented also identifies the potential for under- and over-representation (by country) in the results. The authors have been mindful of this potential in the analysis of the results and the formulation of the recommendations for future work plans, and considers that the results and analysis are still valid and appropriate.

8.1 Data

The survey identified that there is a lack of quality data for input to calculations and models and that there was a consequent need for databases containing appropriate quality data. The need for this data was identified as being in relation to:

- Reliability of fire protection systems
- Smoke leakage of building elements, and
- Material fire properties.

The SFPE Research Roadmap also lists 'data' as one of the four categories under 'tools, applications and methods' (horizontal matrix axis) and identifies the following 'threads' (vertical matrix axis) as being of the highest priority:

- Human Behaviour – demographics
- Resilience/Sustainability – environmental impact of fire and fire suppression activities
- Fire Safety Systems – impact of inspection, testing and maintenance (ITM) requirements on system reliability

There is some overlap therefore between the survey and the roadmap. Notwithstanding this overlap, the authors recommend the following more general workplan elements:

1. Develop an RfP that specifically focuses on identifying and prioritizing data needs for fire engineering purposes and how those priority needs might be addressed
2. Identify opportunities to update (existing), develop (new), populate, host, maintain and fund fire engineering databases – it is assumed that such opportunities would be beyond the means of the Foundation/Society and would therefore follow a 'shared model' approach with industry, academia, etc.

3. Develop formal SFPE guidance on data and databases for fire engineering. It is recommended that such guidance be in the form of a Foundation and/or Society Position Statement (as opposed to a formal SFPE Engineering Guide) on the core elements described in Recommendation 2, namely updating, developing, populating, hosting, and maintaining a fire engineering database.

Regarding availability of data, it is also possible that some respondents are not fully aware of many sources of existing data available from SFPE and elsewhere in publications such as the SFPE Handbook of Fire Protection Engineering [31, 32] currently under revision, the SFPE Engineering Standard on Calculating Fire Exposures to Structures [33] and Guide to Human Behavior in Fire [34]. Other sources of data for verification and validation of models are also increasingly available e.g. FDS validation suite [35] and ISO 20414 Verification and Validation Protocol for Building Fire Evacuation Models [36]. Every opportunity should be taken to promote these to the SFPE membership.

8.2 Guidance

The survey identified that there is a lack of comprehensive guidance [3] regarding the proper use and application of models and that therefore there was a need for suitable guidance to be developed particularly in relation to evaluating safety when making changes to existing buildings and fire protection systems, as well as in selecting appropriate methods for conducting quantitative risk assessment (QRA) of building fire safety.

The Research Roadmap includes existing buildings under the combination of 'design tools' and 'building fires', however it is not given a top priority ranking. The roadmap also has an entire column allocated to 'risk/probabilistic approaches' as one of the four categories under 'tools, applications and methods' (horizontal matrix axis), with top priority being allocated to the following threads:

- Forensics/Investigations – improved guidance for quantifying measurement and calculation uncertainty
- Wildland/WUI Fires – risk assessment of WUI structures

There is some overlap between the survey and the roadmap.

The authors make the following recommendations for workplan elements:

4. Develop an awareness campaign that promotes the importance and requirements of fire model usage guidance
5. Review existing (SFPE [4] and external [5]) guidance on different types of fire model usage and recommend opportunities to revise and improve existing guidance
6. Develop and deliver education/training on fire model usage guidance

[3] The authors use the term 'guidance' to also mean documentation and education.
[4] e.g. SFPE Guidelines for substantiating a computer model for a given application.
[5] e.g. ISO TS 13447 Fire safety engineering – Guidance for use of fire zone models.

8.3 Integration

The survey identified that there is a sizeable gap in the use of advanced BIM by the general design/engineering sectors in buildings (more advanced) compared to those used by fire engineers and that it is not easy to share data between tools. The needs that stemmed from these gaps are:

- BIM/CAD tools/add-ins that provide input data for fire, egress, FEA and hydraulic models used by fire engineers
- Better integration between different fire, egress, building response models used by fire engineers
- The two items noted above are a precursor to providing better QRA capabilities to fire engineers (e.g., Monte Carlo assessments of life safety consequence modelling)

The roadmap does include BIM in two places:

- Under the 'Building Fires' thread and the 'innovative technology/materials' category the under 'tools, applications and methods' header row columns (highest priority for this cell of the roadmap)
- Under the 'Fire Service' thread, "fire department communication with BIM" is nominated, again under the 'innovative technology/materials' category under the 'tools, applications and methods' header row columns. This item is given highest priority for the 'Fire Service' thread

The roadmap also has one mention of model integration:

- Under the 'Human Behaviour' thread, "combined fire and evacuation models" is noted under the 'Design Tools' category as one of the four 'Tools, Applications and Methods' header row columns

There is some overlap between the survey and the roadmap.

The authors make the following recommendations for workplan elements:

7. Develop an RfP to investigate the feasibility and opportunities for increased and improved tool and model integration including:

    BIM/CAD Add-ins generally

    Fire-evacuation models

    Fire-FEA models

    Fire-hydraulic models

    Linkages to QRA models

8. Develop a publicity campaign that highlights opportunities to utilise BIM more frequently and effectively in fire engineering applications

8.4 New tools

The authors had expected a broader range of new model ideas to be identified in the survey, but this did not eventuate, and to some extent this was surprising in that there were no really innovative 'blue sky' suggestions whereas responses were somewhat at the other end of the complexity spectrum.

Future needs were identified as follows:

- Versatile/better radiation models – this was understood to relate to more generalised application of view factor computation (although it is noted that there were several models mentioned by respondents currently being used for this purpose (e.g. TRA and FireWind)
- More standardised spreadsheets for simple egress or other calculations (e.g., parametric fire curve, burnout calculations, etc.)
- Probabilistic models with QRA capability

'Design Tools' and 'Risk/Probabilistic Approaches' are two of the four columns in the 'Tools, Applications and Methods' header row of the Research Roadmap, so there is overlap with regard to QRA models between the survey and the roadmap.

The authors make the following recommendations for workplan elements:

9. Establish a Working Group to undertake work to identify and prioritize needs for hand-calculation/spreadsheet methods
10. Engage with international academic institutes to include priority topics as post-graduate student projects to develop spreadsheet tools
11. Develop an RfP that specifically focusses on existing QRA models and usage in fire risk assessment applications and which links to the content of the SFPE Risk Guide

8.5 Physics and conceptual submodels

The improvement and development of physics and conceptual submodels needs were identified in the survey to better address:

- Sprinkler spray interactions with fire
- Pyrolysis and charring, flame spread, toxicology, soot deposition, gypsum calcination
- Elevator use and human behaviour
- Combustible dust fires, flash fires, explosions and water delivery calculations

The Research Roadmap assigns top priority in the 'Fire Dynamics' thread to "practical models" for a range of phenomena under the "Design Tools" column in the "Tools, Applications and Methods" header row, so there is reasonable overlap between the survey responses and the roadmap.

The authors make the following recommendations for workplan elements:

12. Establish an SFPE Working Group to investigate the state-of-the-art with regard to submodel usage in broader fire models and to identify and prioritize opportunities to both improve/enhance existing submodels and to develop new submodels where gaps exist

13. Based on this prioritisation, develop an RfP as required to address both existing and new submodels

8.6 Regulation

The primary future need identified in the survey under this category was that for automated code-checking [6] tools. This issue is not identified in the Research Roadmap. Nevertheless, the authors believe that there is opportunity to at least explore this area of fire engineering tools further, albeit any such tools are likely to be jurisdictionally specific, and also very vulnerable to quickly becoming obsolete as code update cycles occur.

The authors make the following recommendations for workplan elements:

14. Engage with fire engineering sector to investigate need and/or feasibility for 'code-checking tools'

15. Based on outcome of this investigation, develop and RfP that systematically investigates the feasibility of developing and implementing 'code-checking' tools and identifies similar initiatives that may be occurring internationally

16. If appropriate, develop a pilot 'code-checking' tool and a case study to demonstrate feasibility and application in a real-world environment

8.7 User experience

The survey identified inefficient use of models and software due to time-consuming pre- and post-processing of input and output as the primary existing gap, with the associated need being the improvement to existing user interfaces and more useful presentation of outputs and results.

The roadmap did not identify user experience as a research need, which is not surprising. However, the authors believe that there are opportunities for further work to be done in this area on behalf of the Society's membership, and therefore makes the following recommendations for workplan elements:

17. Establish a Work Group to identify and investigate opportunities to improve the user interface experience of model users

18. Develop a document that describes the standard features required for a model user interface With reference to Recommendation 22 listed subsequently, it is envisaged that details of the standard features for a model user interface will form part of the content of a proposed SFPE Engineering Guide on fire engineering tool usage.

19. Develop an RfP to investigate existing examples and opportunities to improve model input/output visualisation, etc.

[6] The term 'code' is used broadly here to represent any relevant Standard, Code or building regulation.

8.8 Validation

While the survey identified a concern that models are being used outside their limits of application, this highlights a need for more effort to be made by both model developers and model users to make use of validation and verification procedures such as the continuous integration processes now in place for the FDS model. This topic also links to the recommendation made above under 'guidance'.

The authors make the following recommendation for the workplan elements:

20. Encourage developers of FSE models to adopt continuous integration processes as part of model development and encourage model users to make use of validation and benchmarking cases to support the applications for which they are using models for.

8.9 Recommendations not linked to survey responses

In addition to the author recommendations linked directly to survey responses, there are a number of more general recommendations that the authors make for workplan elements, as follows:

21. Repeat a fire model usage survey on a regular basis (every three years)

22. Develop an SFPE Engineering Guide which covers all aspects of best-practice fire engineering tool usage, and that includes a current listing of current models, updated on the same cycle as the regular survey. The new Guide should also be developed to complement the existing SFPE "Substantiating a Fire Model" Guide.

    - Approach SFPE Subcommittee for Standards Oversight with recommendations for new work items

    - Establish Task Group to oversee development of new Guide

23. Conduct regular SFPE education/training for fire engineers on best practice fire model usage

24. Regularly promote and publicise best-practice fire model usage to the SFPE membership

25. Engage with SFPE Subcommittee for Research and Innovation to ensure that fire model usage has suitable prominence and representation in future versions of the SFPE Research Roadmap

8.10 Some thoughts on future surveys

We offer a few brief thoughts and learnings resulting from this current survey.

- It may be desirable to develop targeted surveys for different geographic regions as it appeared difficult to reach a large number of respondents in countries outside the connections of the research team.

- Presentation of results could also consider a geographical regional split eg. North America, Europe, Australasia etc.

- The distribution channels should be widened to beyond primarily SFPE mailing lists and LinkedIn social channels and these should be considered early while preparing any ethics application.

- In a future survey, respondents should not be filtered to those that have used fire engineering tools within the last two years, in order to extract potentially useful feedback from those who may still have significant knowledge about particular tools.

- There may be merit in the future to complement the survey with strategic reviews from interviewing selected individuals or through focus groups. This could provide a more in-depth appreciation of fire engineers experiences and needs.

8.11 Prioritization of recommendations

As well as making 25 recommendations in subsections 8.1 to 8.9, in this subsection the authors also identify what they consider to be the top three priority themes (rather than individual recommendations) for future Society/Foundation research and research funding initiatives.

1. Priority Theme 1 – Data
   As noted in subsection 8.1 of this report, the survey identified that there is a lack of quality data (and associated databases) for calculation and modelling purposes. Coupled with data also being a priority topic in the SFPE Research Roadmap, the authors consider that the topic of data should be the highest priority for future Society/Foundation research and research funding initiatives. Furthermore, rather than focus on any one single recommendation for future workplans in isolation, the authors consider that a comprehensive approach should be taken to this topic, and that such efforts be undertaken in a broad, collaborative manner with the key stakeholders and organisations in the sector.

2. Priority Theme 2 – Integration
   As noted in subsection 8.3, the authors provide two recommendations for future workplans relating to 'integration'. Based on survey feedback, of particular concern to the authors were responses indicating that fire engineers are falling behind other design sectors with regard to BIM uptake and usage. In the authors' opinion, this is also consistent with the priority given to BIM in the SFPE Research Roadmap. On this basis, the authors consider that integration should be the second highest for the future Society/Foundation research and research funding initiatives, and that amongst the various integration opportunities identified in subsection 8.3, priority should be given to BIM integration.

3. Priority Theme 3 – New Tools
   As noted in subsection 8.4, the authors make a series of recommendations in relation to 'new tools'. Based on the breadth of feedback from the survey on this topic, and the central role that engineering tools play in the life of fire engineering practitioners, the authors consider that 'new tools' should be the third highest priority for the future Society/Foundation research and research funding initiatives. The authors also believe that QRA tools used in fire risk assessment should be given prominence.

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Appendices

A. Suggested improvement to individual tools

A.1 FDS

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. *A better front end and parallel processing.*
2. *A dedicated editor with tools easing some tasks (t-square HRR curves, combustion chemistry...).*
3. *A good software package which serves our needs.*
4. *Add FED CO and FED thermal to ISO 13571.*
5. *Additional HVAC support.*
6. *Already done some changes : adding more fuel types, other algebraic models...*
7. *In my case, I enter the data from the FDS editor itself, which is tedious, however, entering the data in this way makes it possible for you to look at the parameters you enter and if they are correct. In Spain, the use is not very common of these tools and in some cases that I have verified it is not used correctly (for example they apply pyrolysis).*
8. *Better capture effect of increasing fuel loads vs. ventilation conditions.*
9. *Better importing options for revit etc.*
10. *Better introductory and documentation information. More examples closer to what we are trying to determine with fire models. More documentation on multicore simulations (how to set them up efficiently). FASTER SIMULATION TIME.*
11. *Continue development!*
12. *Continued presentation improvement, BIM.*
13. *Ease of programming, user guides up to date interface (e.g. pyrosim).*
14. *Easier input.*
15. *Enhance visualization options by coupling with advanced tools as ParaVIEW, Tecplot and Python.*
16. *Faster processing time.*
17. *Faster processing, if possible.*
18. *FDS needs a warehouse sprinkler spray model.*
19. *Having its own user interface without relying on third-party software tools.*
20. *Heat Release Rate Per Unit Area difficult to determine for this application.*
21. *I wish it was a better tool for radiation.*

22. *I would like to extent the use of hand calculations the maximum possible instead of CFD or similar (easy to apply, understand, modify and review).*
23. *Improve run times.*
24. *Improve the engine to import 3D IFC models; more data on fire load / fire scenarios.*
25. *Improved interface with 3D software used by other designers to improve the import of complex geometries. Inclusion of adaptive mesh refinement.*
26. *Improved solver for sprinkler impact would be the next natural step, in my view.*
27. *Just keep on swingin'.*
28. *Make it more user friendly and accessible on different platforms that are not DOS based.*
29. *Make it running faster !*
30. *More ability to reduce computation time.*
31. *More accurate sprinkler implementation.*
32. *More clarity about constraints of applications.*
33. *More flexible meshing for non rectangular geometries.*
34. *Processing speed.*
35. *Pyrosim can be difficult to use on larger models and I would like a method to lock building walls, floors, etc to keep them from moving.*
36. *Research on fire sizes and fire signatures.*
37. *Speed of simulation.*
38. *To improve post processing tools (data analysis).*

A.2 Pathfinder

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. *Ability to automatically couple with FDS for movement through smoke.*
2. *Automated coupling walking speed with ambient conditions due to smoke (from fire models).*
3. *Better integration with FDS/Pyrosim. Various aspects are better addressed in FDS+EVAC and STEPS, overall Pathfinder is our main tool though.*
4. *Direct comparison to hand calculation option. Easier Monte Carlo options.*
5. *Easier to use.*
6. *Further improvement in escalator flows for commuter transport hubs.*

7. *I would add many automatics into edition tools. More options that one parameter can be edited in different places - according to context. Also a perspective 3D view is a horrible experience. Whole user interface requires update as it resembles old programs from early 2000's.*

8. *Improve post processing outputs to analyse relevant information.*

9. *Improvements on elevator programming. Ability to converge results with multiple runs.*

10. *Less buggy and a more probabilistic approach.*

11. *Not really, its a good tool.*

12. *Pretty good software package. Biggest issue is running out of licences across the team of 30+ fire engineers!*

13. *Software validation through post fire simulation in conjunction with occupants and firefighters interview and other available information (CCTV recordings, etc.)*

14. *Standardize occupant load calculation format.*

15. *That it include an assessment of the risk level of the simulation results it shows.*

16. *Transparency in default values and assumptions.*

A.3 Pyrosim

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. *A simple click and choose option to cap the HRR at sprinkler activation. Currently, you have to manually cap the HRR by freeze-time control device.*

2. *A simplified way of drawing a plane at a degree, i.e. to simulate a stair with a pitch of 30 deg.*

3. *Adding FED slice file directly into Pyrosim instead of having to add the three components individually. Inclusion of MTR and wavelet error outputs directly in Pyrosim instead of having to use the "record view".*

4. *Allow set of views in pyrosim which would be pre-set in the results.*

5. *Automatic mesh setup and optimisation.*

6. *Better importing options for revit etc.*

7. *Better interfacing with Revit and other BIM tools to make model creation easier or to feed information back.*

8. *Better introductory and documentation information. More examples closer to what we are trying to determine with fire models. More documentation on multicore simulations (how to set them up efficiently). FASTER SIMULATION TIME.*

9. *Capability to easier visualize solid material properties.*

10. *Easier super-imposition of FDS and Pathfinder output.*

11. *I don't use the CTRL feature of the model - I cannot understand the code. I suspect that writing the code in a human comprehensible form may be a bridge too far.*
12. *Improve the engine to import 3D IFC models; more data on fire load / fire scenarios.*
13. *Inclusion of FED slice output. Ability to change control scheme to align with smokeview.*
14. *Pyrosim can be difficult to use on larger models and I would like a method to lock building walls, floors, etc to keep them from moving.*
15. *Remove default settings.*
16. *Smart meshing, faster speed and optimization of simulation options.*
17. *To improve post processing tools (data analysis).*

A.4 AutoCAD

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. *Again, more fire protection friendly and better customer support.*
2. *Built in tools instead of plug-ins for creation of drawings. Linking/X-ref of models can be tedious when only looking to get an overview and is not very user friendly.*
3. *Directional avenue for fire and smoke vs just all cfd. prebuilt data bases.*
4. *Improved interface between Revit and CAD.*
5. *Improvements are already available .*
6. *Increased database, families and references for Fire Engineering Toolsets.*
7. *It should let have an plugin for evacuation simulation.*
8. *It's good for the purpose.*
9. *Make it more user friendly for fire protection and have better customer service.*
10. *None specific - just require other agencies to be more proficient in data management/production of documentation.*
11. *Nothing, works very well.*
12. *Performance Improvements.*
13. *Provision of specific blocks for fire protection (checkpoints, valves, detection centers, etc.). In Spain the application of BIM in Fire Protection Engineering is quite precarious, almost nobody uses it, I intend to introduce these tools, but nobody values it or pays for it.*
14. *Works fine for the limited use I need it for.*

A.5 Hand calculations, spreadsheets for evacuation

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. *Auto calculate merging flow.*
2. *Auto-calculate stair capacity and reduced flow rate upstream.*
3. *Allow for staircases with levels below grade. Allow for staircases with discontinuities in highrise.*
4. *Connect to staircase model.*
5. *It gives online one number and no information about the process.*
6. *More behavior options, use or not use of local knowledge in the building.*
7. *More interactive outputs / interface in e.g. Python.*
8. *More research plz ;)*
9. *Needs basic software to model simple egress from rooms and stairs.*
10. *Nil. They have their limitations and would ask others to use Pathfinder once they are exceeded.*
11. *Nothing, works well and clearly explained.*
12. *Provide the SFPE Handbook model with more examples.*
13. *Research on travel speeds and pedestrian flow.*
14. *Since it's just an equation, I don't really see any improvement in the equation itself. However a better database for the different constants would be nice. For example, table values for pre evacuation times depending on type of building and such. Stuff like that already exist to some degree of course, but even more!*
15. *Spreadsheet, so perhaps a bit more spit and polish on the layout for user-friendliness and presentation ;)*
16. *This is of my own writing - and updated to suit the purpose.*
17. *Update the model with drill data and post fire data; evaluate the safety margin to be taken into account concerning the evacuation times.*
18. *Written into software supported by Mac.*

A.6 CFAST

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. *Ability to show the ceiling jet temperature correlation in the results to verify sprinkler activation is accurate.*

2. *Automation of risk assessment with multiple distributed input values.*
3. *Better toxicology analysis (e.g. HCN).*
4. *Continued work.*
5. *Easier way to handle library of materials, fires.*
6. *Global material properties libraries, instead of having to build each and every one. But the latest visualization upgrades are much appreciated, can't really ask for much more in a zone model.*
7. *I would like to extent the use of hand calculations the maximum possible instead of CFD or similar (easy to apply, understand, modify and review).*
8. *Include flashover transition. Improve monitoring of heat flux to object (planes).*
9. *More data on fire load / fire scenarios.*
10. *More easy to use interface and lose the US notation.*
11. *Pressure solver causes the software to crash in complex models. This could be improved.*
12. *Provide clearer limitations on application field.*
13. *The default value of heat of combustion of the design fire should be changed from 50,000 MJ/kg to 20,000 MJ/kg.*

A.7 Revit

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. *Better integration between Revit and CAD.*
2. *Better integration with fire protection tools and calculations (sprinkler, fire alarm, egress).*
3. *Better text handling. More ease of use similar to AutoCAD. Better tools for connecting riser nipples and other vertical pipes.*
4. *Increased database, families and references for Fire Engineering Toolsets.*
5. *Many common functions from Autocad are available in Revit, however typically simple tasks in Autocad are tedious or confusing in Revit. Quality of life improvements would be great.*
6. *More efficient IFC export.*
7. *N/A at this time. Still learning the capabilities of the tool.*
8. *Plz. more integration natively for fire.*
9. *User interface is complex compared to e.g. Navis etc.*

A.8 Hand calcs, spreadsheets, inhouse tools for risk analysis

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. *Integration of visual simplifications, e.g. certain features from Visio. Built in Monte carlo modules, fault trees and event trees, bow-ties etc. Relating to spreadsheets QRA for fire risk analysis (IR or societal risk), explicit risk comparison between various options, justification of fire engineering solutions (departures from DtS).*
2. *More research plz ;) relating to risk and situations with variations of for example (some examples): fire from an electrical power distribution station in a building, glass breakage and resulting effect, use of egress paths and risk of congestion, risk of explosion, comparative risk of building safety (and more)*
3. *Needs major investment in CAD interfaces to automate key stages e.g. process sectionalisation, inventorisation, Parts Count; also visual presentation of risk results using the 3D CAD model. Relating to - QRA software proprietary to Atkins plc for estimating individual & societal risk on offshore facilities of every sort, plus impairment frequencies for safety critical systems e.g. Temporary Refuge, lifeboats, fire pumps, emergency power generator, etc.*
4. *Needs to be somehow automated and better set up for cell checking and doing uncertainty analysis.*
5. *Use VTT, NFPA 557 and industry supplied ignition frequency data. Need more and better data for very large risks. Also need better fire brigade intervention data as described previously. Relating to - personally developed tools for annualised risk.*

A.9 B-RISK

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. *A clearer guideline on 1:5 ratio between dimensions in x.y.z directions. Guidance on the applications and limitations of the size of ceiling vents. $1m^2$, $5m^2$ or a % of the roof area.*
2. *Better stability for multi room models with a large number of rooms.*
3. *Fewer bugs. Software has a tendency to give errors with multiple vents and when removing rooms.*
4. *Inclusion of multiple tenability paths to check FED in multiple rooms at once.*
5. *Limitations on use and guidance for correct use for complex buildings, atrium and stairwell.*
6. *More accurate modelling of horizontal openings.*
7. *The ability to add multiple extract fans at once - Ie: a 50m3/s extract causes plugholing, so 10 fans of 5m3/s are added instead. Also multiple deletions of extract. Add indicator that plugholing is occurring when mechanical extract is used.*
8. *The removal of errors and bugs which can be frustrating as they appear sporadically.*
9. *User friendly interface and visualisation.*

A.10 Codes, Standards, Handbooks

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. *A design flowchart / diagram to aid use and inform all to ensure steps are not missed realting to tables for suppression system design in BS EN 12845.*
2. *BS 7975-7 event tree. Proper fire data.*
3. *Develop a similar set of tools (similar to NRC's NUREG-6850 and related documents) for other buildings.*
4. *Tables for suppression system design in BS EN 12845. A design flowchart / diagram to aid use and inform all to ensure steps are not missed.*
5. *NFPA 72. Actual program or examples.*
6. *Operational procedure for the use of emergency elevators of the Fire Department of the Madrid City Council. Enable the implementation of evacuation lifts.*
7. *SFPE Handbook. Just continue updating! =) But one thing: the stairs calculation. The base research has a limit of max speed while as the SFPE Handbook has speeds exceeding this. That is not good.*
8. *NFPA 101, 3, 14, 20, 24, 25, 72. Make online code font larger.*
9. *Spain, Fire Risk Assessment Method within the Framework of the Technical Building Code MEREDICTE. There has been a regulatory change in the Technical Code that will lead to an update of the Method with version 2.0.*
10. *NFPA Handbook (De-rating of combustible loads due to enclosure in cabinets or other steel sided structures). This de-rating section has changed locations in the handbook making it harder to ensure accurate calculations using the de-rating factor because previously performed calculations reference a different handbook section. Keep the handbook sections the same for each edition.*

A.11 Hand calcs, spreadsheets, inhouse tools for heat transfer analysis

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. Numerous. Being an in-house project, there are always several improvements ongoing.
2. E.g. quality controlled engineering templates (e.g. as per simplified Eurocode methods). Now everyone needs to develop these in-house.
3. Just keep up with research. Some tools would be nice to not use home made excel sheets.
4. Improve materials database with high temperature data for temperature dependent thermal properties.
5. None. Is fit-for-purpose but not for use by inexperienced engineers.

A.12 Hand calcs, spreadsheets, inhouse tools for heat transfer analysis

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. An established tool, perhaps in a more interactive environment with constantly updated / nicely presented data output using e.g. Python
2. 1. Develop a GUI. 2. Auto calculate Kb for a composition or different ceiling materials in a single building.
3. Needs software for control of basic C/VM2 burnout calculation and limitation on atrium etc.
4. None, are all fit-for-purpose. Used for coarse calcs to get rapid answer, or to scope a problem, or for sanity checks on proprietary fire consequence modelling software e.g. DNV PHAST etc.
5. None, is fit-for-purpose.
6. Nil.
7. Research ftw!

A.13 SmokeView

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. Intuitive user interface. Ease of producing interactive PDFs using videos of CFD output.
2. Continue development. Thunderhead have done great work here.
3. Make the interface more user friendly.

A.14 Hand calcs, spreadsheets, inhouse tools for hydraulic calculations

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. None.
2. New easy to use software.
3. Provide database storage to permit time based comparisons of test results Using Swedish research on water application in l/min per MW, would like a more robust model.
4. It's a simple spreadsheet tool that serves its purpose.
5. It's a simple spreadsheet and does what I require of it.

A.15 HASS

The survey respondents were asked - *What changes or improvements (if any) would you suggest to this tool?* Responses to this question included:

1. None.
2. Better UI for creating and editing.
3. Better user interface.
4. Draw the system in isometric or 3D like some alternative software packages like Canute.
5. Improvement in isometric drawings, it should support drawings in autocad. From a calculation point of view it is the best software there is but it has not evolved for more than 20 years.
6. New Presentation.

B. Influence of AHJ on tool selection

The survey respondents were asked - *Are you aware of any specific fire engineering tools required by the approving authority or regulator for projects that you or your company have completed?*.

- ARICA (it's one of the mandatory tools in Portugal for existing buildings).
- ARICA and Gretner.
- ARICA, Gretner.
- CFD modelling for smoke control system performance; CLT/glulam burnout analysis for high rise mass timber buildings; Radiation exposure analysis for occupants escaping past cooker hobs in open plan apartments.
- Computer-generated hydraulic calculations.
- CAD-based drawing sets.
- CONTAM for zone smoke control.
- CONTAM, FDS.
- Some (few few actually) AHJ's require stair pressurization rational analysis based on CONTAM or similar software.
- Digital seals and signatures.
- FBIM is a fire brigade approved package for calculating response times.
- Some fire officers required us to run CFD in FDS.
- FDS.
- FDS (italian fire code).
- FDS for a special project (this however is an exception).
- FDS is often used for complex projects not covered in the building code. In order to review our documentation, they also need the software, in theory anyways.
- FDS, otherwise - it's really up to the fire engineer to define the appropriate calcs and tools (not the regulator), and, this is how it should be.
- FDS, Pyrosim, Pathfinder.
- Fire brigades having jurisdiction often request to see FDS or egress modelling, and often in excess of what the project actually requires from an engineering verification perspective, but pretty pictures provide a degree of confidence, I suppose, even if the capacity to verify and validate input and output is sometimes lacking.
- Fire Dynamics Simulator.

- NYC requires FDS simulations for cantilever analysis through a building Bulletin. I have also ran into a few other AHJ where we had simple atriums and did hand calculations, they still wanted to see a computer model even though it is not code required.
- Hazardous material inventory data sheets. They are NOT adequate for what the purpose they claim to meet. I refuse to use them and explain why to them. My material is always accepted.
- Hydraulic calculation (spinkler); validation of results (fire pump); basics of installation (sprinkler and pump).
- Hydraulic calculations using HASS.
- I have developed and used spreadsheet based radiation calculations, submitted to approving authority. Similarly, specific egress calculations have been undertaken on spreadsheet for specific projects, and submitted.
- I work for AHJ - constantly use FDS for smoke control system checking.
- In Israel, CFD is required in high atriums, public assembling spaces.
- Manufacturer's software.
- MEREDICTE, PATHFINDER, LEGION, FDS.
- Sprinkcad and Elite.
- The Approving Authorities like fire engineers to follow general calculations and methods to be in line with British Standards or other industry guidances. They do not specifically request use of specific tools. However, they do request more often involvement of third party reviewers who may have access to same tools and software used by initial fire engineer.
- Tools performing the calculations described in standards to which regulations refer.
- NEN 6068 external fire spread through radiation; MR capacity of escape routes; NEN 6093 SHEV capacity; CFAST/OZONE/homebrew alternatives for smoke logging of large compartments.
- Trip time analysis tool for 750 gpm plus dry systems.
- Without specific names, AHJs typically require some sort of fire modeling to support performance-based design. It is however left to the FE to select appropriate tools.

C. Gaps and future needs from survey respondents

The survey respondents were asked - *Based on your knowledge and experience, what gaps exist in current fire engineering tools or what new tools should be developed?*

C.1 Data

1. **Input data.** *The greater challenge in the use of every tool is to find references for input data. An international database would be of great help for everyone in the fire community.*
2. **Input data.** *More comprehensive (realistic) leakage data of building elements based on door fan testing would be helpful in smoke control modeling.*
3. **Input data.** *Reliability of fire protection equipment such as fire shutters, fire curtains, smoke curtains. Developed Design fire data base software.*
4. **Input data.** *Solid data that can be used in fire models to simulate fire situations.*
5. **Input data.** *The main gap is to develop fire scenarios more systematically with the help of reliable data (failure on demand of systems...).*
6. **Input data.** *The main gap is in the quality of the input data.*
7. **Input data.** *Comprehensive material property databases and MSDS information.*
8. **Product data.** *material combustibility/smoke information and ratings for hazard classification.*

C.2 Documentation, guidance and education

1. **Model documentation.** *Any software should come with a detailed manual to explain not only how to use the tools, but background and general assumption. Ideally this manual is accessible to anyone so that also Statutory Authorities can have insight into background, assumptions, potential restrictions of applications etc.*
2. **Guidance on application of models.** *I think the knowledge gaps are more related to how the tools are applied. I see designers rely on their calculations and modelling as being specific and exact answers. In my view, they are approximations of behaviour (of people, smoke, fire) based on a series of estimated input parameters and calculation methodologies based on observed behaviours.*
3. **Evaluating safety in existing buildings.** *A guide is needed to support Fire Protection Assessments for existing buildings. Intent would be to better understand, characterize, and address non-compliances that don't represent a substantive risk and judgements to support if there is a robust maintenance program even where deficiencies might be present.*
4. **Comparing safety levels.** *A guide assisting fire protection professionals in the establishment of compensatory actions. (i.e., Is a roving fire watch really equivalent to an automatic water-based suppression system, and if not, how much protection is actually being provided?)*
5. **Fire scenarios and design fires.** *Additional information and guidance on fire scenarios and fire sizes.*

6. **Evaluating safety in existing buildings.** *Guides / flowcharts for existing systems modifications.*

7. **Guidance on application of models.** *Some tools are outdated but still useful, such as the original zone modeling software that preceded CFD models. It would be good if older tools can still maintained as a useful tool for training of associate engineers and better their understanding and knowledge of compartment fire modeling. In-house spreadsheets that are not-considered could be maintained in a central SFPE or similar database for public use. One of the largest gaps in the application of these tools are misapplication by users. Adequate resources and awareness should be available regarding the importance of peer review and guidance on proper application of tools, particularly CFD fire modeling.*

8. **Understanding the model.** *There is a learning curve for many of the tools. Fire and Egress modeling require a knowledge of what you are studying as if you put garbage in you'll get garbage out and I feel this is a largely overlooked area.*

9. **QRA models.** *There are plenty of validated tools for fire consequence modelling. What the sector lacks is an appreciation of the type of models needed to conduct a fire QRA for a building. This is because the sector does not know what QRA is, or how to do it. The proposed new ABCB Part A8 risk acceptability criteria have example QRA studies that other sectors would not consider valid. The concept of Design Fires is badly flawed, the overall performance of a building cannot be established from a handful of user-selected fire scenarios and conditions. The QRA model for a typical offshore oil platform with a POB of (say) 150 souls, will involve circa 5,000 base scenarios for 10 million unique risk calculations. A recent QRA for a large onshore LNG facility with a variable workforce of 400-1350 people has about 70 million unique risk calculations. Each calc describes the harm caused by a specific scenario under specific conditions at a specific time. A building fire QRA must do the same so suitable consequence models are needed.*

10. **Technical training.** *Basic on line technical training for sprinkler, fire pump, for those who are not in this industry, but want to learn.*

11. **AI and machine learning.** *There is virtually no talks on AI and machine learning.*

C.3 Integration

1. **Use of BIM.** *Egress modelling are currently very deterministic - New tools should incorporate the use of BIM models if possible.*

2. **Coupling models.** *Comprehensive simulation tool that drawing relevant data from BIM or other formats - and additional data where needed - can assess life safety, simultaneously taking into account all of the following: 1. fire and smoke development and spread, based on standardized interior (furniture / finishing etc) scenarios for the specific uses 2. fire suppression (mostly sprinklers) systems reaction and interaction with the fire (1); 3. building response in relation to (1) and (2) - structural members, fire compartments etc 4. egress calculation in relation to 1, 2 and 3. There are some tools for some of the above, integration is what is needed and I understand, quite hard to achieve.*

3. **Automating inputs.** *Automatically generating models (various systems) from building plans would be helpful for many projects and in many different tools.*

4. **Use of BIM.** *Fire engineering, or fire safety documentation, should make its way into BIM (Building Information Modelling), where all the other design disciplines work and coordinate. The Fire Engineer's deliverable is typically a report that then has to be interpreted by others to make its way in to the design documentation.*

5. **Visualisation tools.** *FDS is a great tool but visualisation part is lacking flexibility. Smokeview is capable of features but has a complex interface. It could be improved. Pyrosim results tool is able to read smokeview files but does not have all features that Smokeview has.*

6. **Coordination.** *Correlation between installations layout (pipes, cables, smoke exhaust pipes)*

7. **Use of BIM.** *I think that there is a gap between the tools we use in the community (B-Risk, FDS, etc.) and the tools that are now used by other disciplines (e.g. architecture, mechanical/electrical/civil engineering) in construction sector (AutoDESK BIM for example). I think that a priority for the fire community should be to close this gap through innovation and development.*

8. **Risk.** *Incorporation of risk.*

9. **Use of BIM.** *Add-ins to BIM software (Revit) for fire safety design.*

10. **Coupling models.** *Better integration of material properties to smoke composition to occupant exposure to egress models.*

11. **Structural models.** *Tools for global structural analysis incorporating all interfaces, fixings, flanges, bolts. (preferably compatible directly with TEKLA models or similar structures software).*

12. **Coupling models.** *Refined interfaces linking egress and fire modelling with consequence assessments (FED/FIC etc).*

13. **Use of BIM.** *The gaps are whether people understand how the tools are used and applied. The new tools needed are related to the evolution of Building Information Management and how the I works. Further, the evolution in technology application in A/E is so removed from Fire, the fire industry risks being left behind.*

14. **Use of BIM.** *Standard for fire safety in BIM.*

15. **Suppression system design.** *All gas based and water based design flow calculations in one tool.*

16. **Coupling models.** *A linked model which incorporates fire models and egress models together would be useful for more complex projects especially involving travel through smoke. At present there is an approximation which can be done by manually coupling a fire model results (FDS) to an egress model (Pathfinder) but this is quite a manual process.*

17. **Linking Revit and BIM.** *The biggest gap is linking hydraulic calculations to Revit. Almost no sprinkler designers use Revit because there is no link.*

18. **Linking Revit and BIM.** *Revit tools for fire protection significantly lagging behind the rest of the industry. Especially ability to locate sprinkler heads and defining different symbols for different heads. Fire protection Revit families must be obtained through manufacturers websites to be usable. Little or no built in families exist like what is provided for MEP.*

19. **Coupling models.** *2 way coupling FEM-CFD.*

20. **Coupling models.** *The ultimate would be the ability to model egress and fire development in the same model.*

21. **Coupling models.** *Better integration egress-zonemodels/cfd.*

22. **Libaries.** *Graphics and material libraries.*

23. **VR technologies.** *It would be interesting to combine the numerical simulations and BIM and further relate and integrate with VR technologies.*

C.4 New Tools

1. **New tools.** *My team of engineers have used numerous tools in the past. We even developed the Sebench App that is available for free in the iphone and google app store. (We are open to letting this go if you want to expand on the software). Also Meyer Fire has a large set of tools that is readily available.*

2. **Fire service operations.** *Tools to evaluate firefighters response time and effectiveness, that can be easily adapted to different countries/cities based in the type of Fire Brigade, equipment and personnel; more data about real fires with proper post-fire analysis (fire and evacuation simulation, time line, temperatures developed, number of casualties and cause of death, number and type of injured, etc.)*

3. **Egress.** *Simple building evacuation tool, generalised so that it is not geared to one national regulation system only, with control over parameters such as: flow capacities, route choice, realistic phased start of movement, stream merging.*

4. **Risk.** *Tools or parts of tools enabling risk informed analyses: systematic variation of input variables, entry as pdf of distribution of input.*

5. **Detection.** *Smoke detector activation times, ASET/RSET, hydraulic calculators.*

6. **Failure analysis.** *I haven't seen any software that is capable of cascading failure analysis.*

7. **Radiation calculations.** *I would like access to radiation software. We have Firewind which presents only some of the values. I am presently trialling TRA but input is not as straightforward. I no longer have access to in house spreadsheet that was a good tool for input and output.*

8. **Radiation calculations.** *A tool that predicts the radiant heat transfer from multiple emitters onto a finite area receiver, with different orientations, such as acute/oblique angles, where 'traditional' view factors are not readily available.*

9. **Radiation calculations.** *A better tool to measure horizontal fire spread would be extremely useful. At present we mainly rely on in-house spreadsheets which use the view factors from the SFPE handbook. but sometimes these are insufficient, especially for more complex geometry, or for multiple radiating elements at angles other than parallel.*

10. **Risk.** *We have our own spread-sheet for risk assessments and I feel like we would benefit from software with better user interface as it would limit link errors and increase repeatability between projects. We are, however, not aware of any software which is available, relatively cheap and user friendly as we have all only been taught in Excel.*

11. **Design fires.** *Tools to calculate the development of the fire source (HRR in time, based on fire spread calculation)*

12. **Extinguishment.** *I miss programs for calculating the flow of extinguishing gases. On the other hand, I understand that we are engineers and that we can do many designs from spreadsheets. Problems can appear when the approval of the programs is required, which in Spain only large companies ask for.*

13. **Risk.** *Tools for assessing fire risk in industrial use as well as risk assessment methods for historical heritage and business continuity should be developed.*

14. **New tools** *Tools are available for almost any analysis we need to conduct. Where tools are not available, we can generally create a spreadsheet which calculates the required information from the applicable inputs. It would be beneficial for a more up to date package of software to be available which collates all common tools into one interface, similar to the old Firewind package, but there are workarounds to this.*

15. **Spreadsheets.** *Spreadsheets for hand calculations.*

16. **Spreadsheets.** *A single Excel suite/calculation software with various built-in tools for hand calculations of egress, structural assessments and QRA / risk visualizations. At the moment, these are mostly individual templates/tools.*

17. **Simpler tools.** *A middle ground evacuation tool that provides more complexity than an excel spreadsheet but not as complex as Pathfinder. Other tools are available but their user interface is not friendly.*

18. **Simpler tools.** *Some tools (like FDS) are too complex for normal fire engineering applications. That type of detail is maybe required for research applications but not for a study of tenability in a project.*

19. **Radiation calculations.** *Updated Firewind (or similar) radiation tool with usable graphics for inclusion in fire engineering design reports.*

20. **Spreadsheets.** *Sometimes I think it may be easier to have a spreadsheet with a bunch of tabs with difference calculations than individual tools.*

21. **New tools.** *Easier tools to calculate radiation, pool fires, and other fire risk analysis scenarios in industrial/hydrocarbon settings.*

22. **Spreadsheets.** *Probably a new set of Excel spreadsheets for first cut calculations of fire phenomena before CFAST/FDS types of analysis.*

23. **WUI fire.** *That's a good question... A better prescriptive tool to analyze: Wildfire risk, Wind turbine fire exposures.*

24. **Facades.** *Simple tools for estimating exterior fire propagation on facades.*

25. **Risk.** *Automated fire risk assessment methods should be a top priority as a new tool for building fire safety analysis.*

26. **Mass timber.** *CLT/glulam structural fire engineering modelling software.*

27. **New tools.** *It really depends, especially when you are targeting specific audience. Oil and gas operators love to see the beauty of how effective the fire protection system when it's put into perspective of real life challenges-it can be unignited gas release, fire and gas detection and water spray but in possibly simpler model.*

28. **Hydraulics.** *Still looking for better fire sprinkler system hydraulic calculation tools.*

29. **BLEVE.** *Still looking for better BLEVE calculation estimation tools.*

30. **Risk.** *Still looking for better operational risk assessment tools for various occupancies.*

31. **Risk.** *Risk based analysis tools.*

C.5 Physics and conceptual model

1. **Sprinkler interactions.** *Also, there is currently a gap in accurately estimating/modelling the impact of sprinkler activation (suppression of fire growth, pressure reduction, 'scrubbing' of combustion products, hot layer temperature reduction) wherefore conservative estimates and assumptions have to be made, consistently underselling or underestimating the value and benefit of sprinkler protection.*

2. **Sprinkler interactions.** *Effect of sprinkler water spray on smoke behaviour.*

3. **Sprinkler interactions.** *We would benefit from a model that is capable of modelling sprinkler interactions with fires, especially with regard to reduced buoyancy in the plume.*

4. **Sprinkler interactions.** *Sprinkler models.*

5. **Sprinkler interactions.** *A proper way to model the fire development in a room with sprinklers.*

6. **Sprinkler interactions.** *The single biggest gap in my field is validated sprinkler spray data for warehouses.*

7. **Sprinkler effectiveness.** *Sprinkler effectiveness.*

8. **Flame spread.** *Fire spread tools. FDS almost has it all. If it were able to predict or calculate flame spread depending on e.g. material properties and had a better model for radiation, it would be unstoppable. As far as the simulation time goes, it would be worth it anyway.*

9. **Elevators.** *Elevator simulation has many shortcomings that must be addressed. Heavy results of multiple simulations. Not free or not available for limited use for software research purposes. Poor validation. Elevator problem.*

10. **Heat transfer.** *Improved modeling of heat transfer through structural assemblies like floors or walls.*

11. **Human behaviour.** *Introduce more behavioural situations and let them be not so rigid and user defined. All agents have strictly defined behaviour, there is no possibility to change the goal / path during simulation. Especially while simulating events that happen during the evacuation - like sudden block of the door for evacuating crowd.*

12. **Hydraulics.** *Dry pipe system water delivery time.*

13. **Physics.** *Better handling of pressure related effects of fire for confined room with mechanical ventilation in zone model.*

14. **Pyrolysis.** *Models for pyrolysis of solids and evaporation of liquids need to be improved.*

15. **Elevators.** *Egress models/assumptions for lift based evacuation.*

16. **Mass timber.** *Delamination of timber/wood products.*

17. **Faster solvers.** *Hard to describe it shortly, but here is my best try at a single-sentence summary: Less fancy visualisation, more accurate physics and faster solvers.*

18. **Fire growth.** *Prediction of fire growth.*

19. **Flame spread.** *Prediction of flame spread.*

20. **Physics.** *Better toxicology analysis. Better sub-models for production of "fire patterns" including soot deposition, calcination of gypsum wallboard, and charring of wood.*

21. **Explosions.** *Risk analysis tools for explosion hazards.*

22. **Suppression.** *There aren't any tools that I'm aware of that calculate extinguishing agent concentration for gas suppression systems using different extinguishing agents such as Novec 1230, Carbon Dioxide, Inergen, etc. There also aren't any tools to calculate pressure relief in structures based on the building construction. I've managed to get tools from a contractor but it's specific to the equipment they use.*

23. **Industrial hazards.** *Over the past decade I have focused largely on the evaluation of combustible dust fire, flash fire, and explosion hazards. Compared to the tools available for more traditional fire protection engineering problems, there is very little available for combustible dust. Tools that could better quantify dust suspension / entrainment in buildings and equipment, dust cloud combustion, ignition hazards, and deflagration effects (e.g., pressure / pressure piling, deflagration propagation, fireball dimensions and associated heat flux) would be very valuable in my practice. Computational tools such as the DUST-EX module within FLACS have some capability, but is still quite limited. Additional research on these topics and public-domain software would be very useful.*

C.6 Regulation

1. **Educating the AHJ.** *I believe the biggest issues are: - education of approval and referral authorities, so that they know what they are seeing and what they should be scrutinising. Some engineers simply 'do FDS' because they know it will be accepted, rather than (a) questioning if it is the best / most appropriate tool for the job or (b) using quality inputs..... Based on this I believe a short document on when to use programmes like FDS and critical inputs should be handy for the industry (eg. Produced by Society of Fire Safety at Eng Aus or SFPE guide, etc) - critically it would need to be short, simple and clear language that approvals authorities could use to clarify with engineers why certain inputs have been used.*

2. **Demonstrating compliance.** *Automation of code compliance review in 2D/3D software (travel distances, number of exits, widths etc.) Autodesk are still trialing this.*

3. **Demonstrating compliance.** *To align with local AHJs.*

4. **Demonstrating compliance.** *A tool that looks across all codes and standards for a searched topic to help with determining the different requirements for a project in a jurisdiction.*

5. **Demonstrating compliance.** *Better tools for Eurocode 3.*

6. **Demonstrating compliance.** *Egress and Burnout calcs to C/VM2. Engineers all create own spreadsheets very difficult to validate as a peer reviewer. Also FED (CO) real time calculation for movement through spaces.*

7. **Demonstrating compliance.** *The frustrating part of our industry is the constant change of standards you think are set in stone. How does FM Data Sheet 7-29 change so much. It's really not a prescriptive standard but based on some prescriptive fire testing and a lot of assumptions. It's frustrating to tell a client that their fire protection system was adequate in 2017 but the standard changed in 2020 and now it's not adequate. It makes our industry look bad.*

8. **Accreditation.** *An accreditation protocol for CFD model users is necessary to implement results of these simulations into forensic investigations.*

9. **Demonstrating compliance.** *Ref BSEN 13501, 476 etc, assessing materials and composites fire capabilities, FDS can do this but results are not always consistent with practical fire tests.*

C.7 User experience

1. **Cost.** *I think that the tools that are being developed in the area of simulation analysis should be more divulgated and transmitted freely for a period time, in the view of testing the solutions that are being implemented in complicated projects.*

2. **Ease of use.** *Need more friendly user software.*

3. **Ease of use.** *Ability to use Notepad or Excel to edit HASS or Contam input/output as needed. Better output from Contam (the output files are a mess of spaces that are very difficult to parse with programs like Excel).*

4. **Faster solvers.** *Faster FDS modeling for preliminary estimates prior to full-length modeling (larger time steps for a rough run).*

5. **Use of BIM.** *Better tools in Revit and faster Revit files in general.*

6. **Better interfaces.** *At present, I believe most platforms for analysis already exists. It's more a question of features and creating a better interface. I also embrace open source and would like to see an effort to develop tools such as opensees or calculix for FE-analysis. I therefore also like openfoam and firefoam even though FDS is easier to use and has a better validation suite.*

7. **Information management.** *Information management and analytics could be vastly improved for practical application by end users.*

8. **Web tools.** *Transition from spreadsheet-based tools to web-based / Python-based tools with nicer outputs.*

9. **Cost.** *Affordable and user friendly software for special analyses such as egress modelling and fire modelling suites.*

10. **Cost.** *The current fire modelling software is expensive and time consuming to use. It is difficult to verify that it is being used correctly and errors in output difficult to detect.*

11. **Ease of use.** *Simplify FDS inputs, even Pyrosim is clunky.*

12. **Communicating results.** *Representation of results is still relatively poor. We are constantly trying to improve it to communicate our results to our customers and improve explanation to authorities.*

13. **Ease of use.** *Most lack practicability and easily understood. Hydraulic calculation.*

14. **Ease of use.** *Much easier predetermined fire types based on occupancy would be great for performance based design tools.*

15. **Better interfaces.** *A further improvement in front ends of the tools would make the tools more efficient and user friendly.*

C.8 Validation

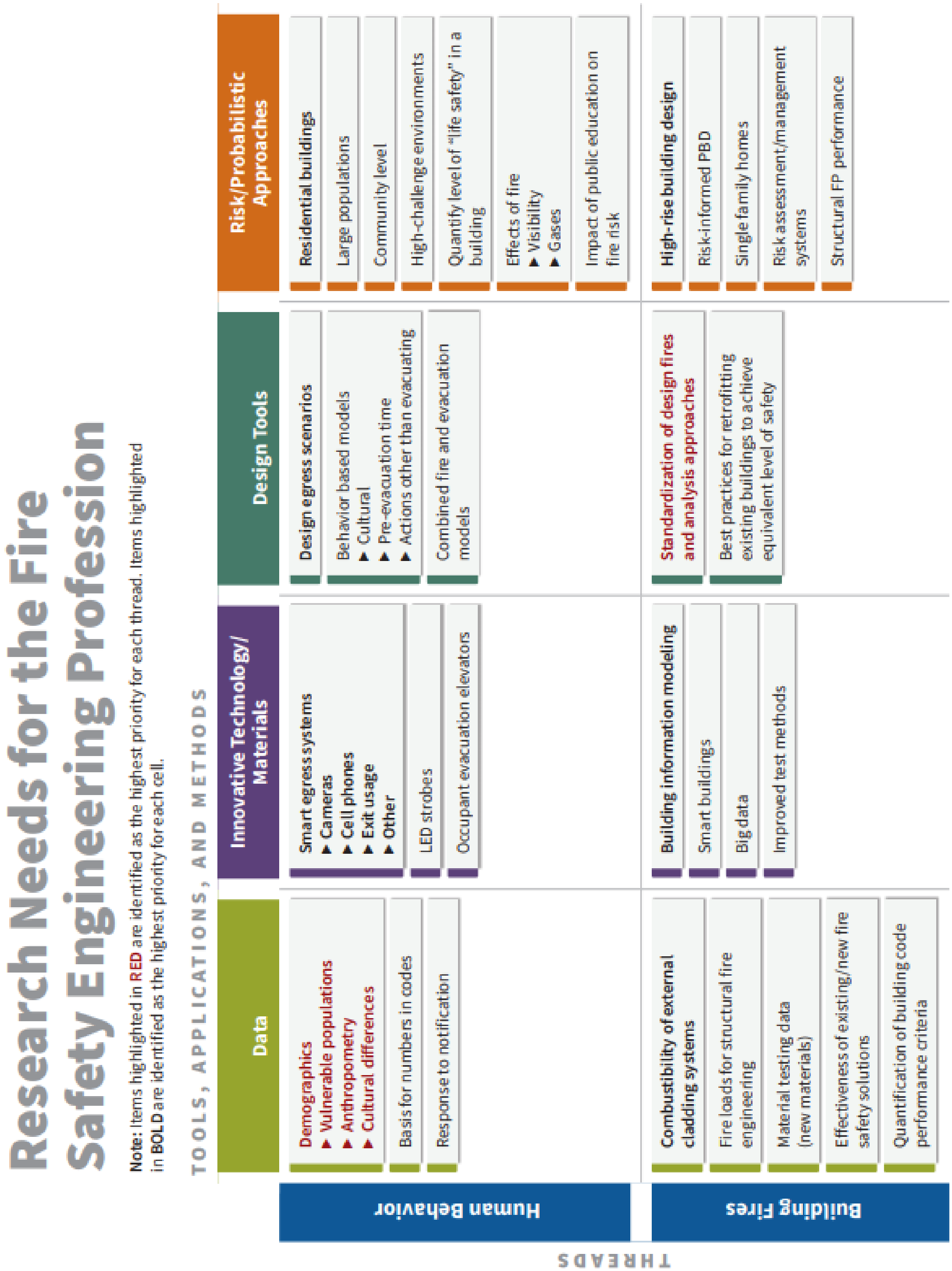
1. **Validation.** *In many computer based "tool" as you seem to like to refer to programs, the background of the program has not been investigated by the operator to verify it is properly programmed and therefore providing accurate output. A large portion of my work in the design area is for structural fireproofing design for areas for which there is no Listed Design system. In other words, I prepare a lot of Engineering Judgements for structural fireproofing and firestopping systems. This is all done with research and a lot of background in the subject area. My work in fire alarm and fire sprinkler systems is very small to none at the point. I have been in business for 34 years.*

2. **Validation.** *Validation of the tools in combination with regulation in the member states.*

3. **Validation.** *Tools are often used far outside their field of validated application. Users of the tools could profit from concrete guidance on how to proceed, what accuracy they can claim, including when not to apply the tool. Important parts of tools are black boxes, it is not possible to know which algorithms the model uses. That makes it impossible to have informed confidence in the results. Engineers should only use tools of which all content is open for scrutiny when needed. Guidelines / rules should require that feature, only then will tool developers put the effort in providing the information.*

4. **Validation.** *Many are based on empirical correlations that have long since been separated from their original statements of range of validity and application, as well as the details of how they were obtained (limits, assumptions, etc.). This opens the issue of potential extensive extrapolation of results except when used by the very well attuned user. Either better charting of the tools or better education of the user or both (ideal) is called for. Fire performance ranking data (I.e. standard based test data) is being used without due regard to the limits of the test apparati which were never designed for quantitative determination of many of the 'deduced' parameters obtained during a ranking test. This calls much input data into questions across many tools!*

D. SFPE research roadmap



TOOLS, APPLICATIONS, AND METHODS

THREADS	Data	Innovative Technology/ Materials	Design Tools	Risk/Probabilistic Approaches
Resilience/Sustainability	**Environmental impact of fire and fire suppression activities** Cost of fire events Cost/benefit of different types and multiple levels of FP measures Environmental impact of fire testing Quantification of structural fire resilience Flame retardant toxicity	**Assess fire hazard of new sustainable building materials/ practices** Identify/quantify sustainability benefits of smoke control systems and natural ventilation Evaluate fire hazards of new sustainable energy technologies Evaluate fire hazards of flammable refrigerants Life expectancy of installed fire protection systems Determine appropriate suppression systems for new technologies	**Development of design tools/ best practices for fire safety engineering for resilient systems/buildings** Analysis of impact of climate change on fire safety Cost-effective and resilient FP practices for developing countries Post-fire seismic behavior Identification of critical fire protection aspects for disaster reliability	**Development of risk-based analysis to compare hazards of fire to long-term health impacts of fire mitigation measures** Risk- and reliability-based methods for ITM of fire protection systems ▶ Preventative and predictive maintenance ▶ Human impact on ITM reliability ▶ Reliability of water supplies ▶ Reliability of installed equipment
Fire Service	**Exposure tracking from incidents** Data-driven fire inspection scheduling Improved injury, holistic fatality data collection and economic analysis Impact of WUI on fire service Naturally occurring events ▶ Rate, severity ▶ Fire as a secondary impact	**Smart firefighting** **▶ IoT integration** **▶ Mechanical augmentation** **▶ Fire department communication with BIM** **▶ Firefighter tracking and location** Automated, quantifiable exposure monitoring Firefighting PPE and tools ▶ Firefighting and fire apparatus cameras for investigation/ debrief	**Model fire department response leading to better models of** **▶ Reverse evacuation** **▶ Egress/ingress** **▶ Duration of water for FP systems** **▶ Structural collapse** **▶ Firefighter response recreation and training aids** Compare/contrast tactics internationally to determine impact of firefighting/construction differences on fire growth/severity	**Evolving building technology and fire suppression tactics (effect of smoke/heat ventilation)** Firefighter injuries ▶ Effect of understaffed apparatus on individual personnel ▶ Fire ground safety ▶ Long-term exposures on individual personnel Effect of firefighting interventions on occupant risk New vehicle technology and fire suppression tactics Lessons learned to reduce risks in developing countries Tactics and training for emerging technologies

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TOOLS, APPLICATIONS, AND METHODS

THREADS	Data	Innovative Technology/ Materials	Design Tools	Risk/Probabilistic Approaches
Fire Dynamics	**Material properties** Fire dynamics of large compartments Test data archiving Model stewardship Toxicity data Sprinkler data	**Standardized/accepted approach for developing material properties** Retardant behavior Massively parallel computing Mesoscale Extreme ambient conditions	**Practical models for:** ► **Pyrolysis of complex materials** ► **Extinction and reignition** ► **Sprinkler suppression** ► **Underventilated combustion** ► **Glass breakage** ► **Human consequences** ► **Deflagrations/detonations** Realism in test standards	**Ignition frequencies** Probabilistic distributions of heat-release rate curves Fire spread models Fire frequencies
Fire Safety Systems	**Impact of ITM requirements on system reliability** FP systems performance data Evaluation of new and existing active FP systems efficacy ► Suppression of unique and emerging hazards ► System design criteria ► Smoke control system Evaluation of passive FP systems efficacy Evaluation of durability of FP systems Gaseous fire suppression systems applied to high air flow environments	**Integrated FP systems and building connectivity** Efficacy of detection, alarm, communication systems Protection of storage ► Automated ► High challenge Reliability of detection/alarm/ communication ► False positives ► Failure on demand ► Failure modes due to extreme environments	**Corrosion protection design best practices** Guidelines on suppression effectiveness at various heights FP System design ► Atrium protection and modeling ► Smoke control systems ► Passive FP system design and test methods	**Adequacy of passive fire resistive construction** Evaluation of ► Smoke control systems impact on reduction of risk of losses ► Adequacy of passive fire resistive construction ► Effectiveness of fire stop installation by multiple trades versus certified technicians ► Life quality indices to assess FP performance Reliability of ► Water supplies ► Suppression systems failure modes, aging, and complex systems Relationship between safety, security, and routine operations Matching reliability of installed systems with risk assessment

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TOOLS, APPLICATIONS, AND METHODS

THREADS	Data	Innovative Technology/ Materials	Design Tools	Risk/Probabilistic Approaches
Forensics/Investigations	**Persistence of burn patterns under different compartment fire conditions** Building material properties as inputs for fire models Fire effects on building electrical systems/components Evaluation of incident heat-flux profiles from non-standard fuels Damage resulting from heat radiation and blast waves on buildings, industrial assets, etc. Digital recordings of distributed control systems and programmable logic controllers Digital data collection (black boxes) Status and data related to availability of FP measures during event	**Improved tools for obtaining building dimensions and fire sizes from photographs and video** Use of cloud-based home/ consumer devices to pinpoint fire origin Linking of 3D scanning technology with computer fire models Overview of large scenes from drones Data mining to identify chemical process deviations Methods to preserve evidence Tools to extract data from digital sources	**Improved software to create multiple-source dynamic event timelines** Tools to evaluate impact of ventilation on compartment fires Simulation tools to recreate process conditions in chemical plants Advanced calculation methods to evaluate hypothesis Tools to estimate damage effects Virtual reality/augmented reality to describe and test scenarios	**Improved guidance for quantifying measurement and calculation uncertainty** Repeatability of fire test measurements Root cause analysis methods and tools Causes and causal mechanism analysis Human error assessment methods and tools
Wildland/WUI Fires	**Impact of firebrands** Fire hazard identification and quantification Ignition of WUI materials Fire behavior and fire spread Emissions and health effects Fire ecology and long-term effect Data to support WUI codes and standards	**Building fire protection in WUI** Wildland/WUI fire damage mitigation Warning and notification Remote sensing and communications	**Design against exterior building fires** Wildland/WUI fire modeling Firebrand ignition prevention Fire behavior prediction tools Resilience design tools Landscape planning tools	**Risk assessment of WUI structures** Risk of combustible fuels in WUI/wildland Assessment of risk, effectiveness, and economics

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TOOLS, APPLICATIONS, AND METHODS

THREADS	Data	Innovative Technology/ Materials	Design Tools	Risk/Probabilistic Approaches
Non-Building Fires	**Data for hazard identification/ reliability/severity/frequency (industrial)** Alternative energy generation PV installation fire spread Petrochemical fire incident frequency Causes of vehicle fires	**Energy Storage** ▸ **Containment for new products/damaged products** ▸ **Higher reliability manufacturing/more resilient product design** ▸ **Safer energy storage chemistries** ▸ **New inspection techniques** ▸ **Self-monitoring of equipment** ▸ **Safe transportation** Improvements to petrochemical equipment safety Tunnel fire suppression	**Product safety standards** Installation Standards ▸ ESS ▸ Oil/gas drilling CFD fire models (tunnels/ underground, tank fires Design considering first responders (ESS, vehicles, tunnels) Heat transfer models for energy storage cell design Tunnel evacuation/fire models Models for use in siting and design of tank farms Tunnel design fires	**Improved identification of high-risk industrial facilities** Improvement of risk management practices at chemical facilities

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LIST OF ACRONYMS

BIM – Building Information Modeling
CFD – Computational Fluid Dynamics
ESS – Emergency Storage System
FP – Fire Protection
IoT – Internet of Things
ITM – Inspection, Testing and Maintenance
LED – Light Emitting Diode
PBD – Performance-Based Design
PPE – Personal Protective Equipment
PV – Photovoltaic
WUI – Wildland Urban Interface