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Fire risk assessment tools for the built environment - An explorative study through a developers' survey

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ABSTRACT

In the built environment, often too much focus is put on compliance instead of seeking the optimal fire-safety solution for the building. Because of a lack of tangible incentives for building owners, the benefits of implementing fire safety measures and their societal contribution are often not recognized and therefore, not considered. By means of a literature review and a survey, we have indicated necessary fire-safety related attributes and tool features and analyzed the currently available fire risk assessment tools. This study shows that a limited number of these tools can provide a partial fire risk analysis of a building. A total of 26 tools were found. No tools were found that included all the identified fire consequence-related attributes to ensure fire-safe buildings. However, we did identify 11 tools that have the potential to assess between 32 % and 52 % of the found attributes of building fire safety. To stimulate the development of such tools, this paper provides 12 factors by which to assess fire risk assessment tools – quantifying the overall 'quality' of the assessment tool – which can incentivize industry to refine the existing ones with enhanced predictability of the potential consequences of fire incidents.

1. Introduction

Recent developments such as the energy transition and aging of the population call for the integration of new technologies into new and existing buildings, e.g., robotics, stairlifts and solar panels. If no additional mitigation measures are incorporated, installing such equipment will increase the overall probability of a fire occurrence. As called for by the Society of Fire Protection Engineers (SFPE) in their research roadmap [1], more tools are needed for the Fire Safety Engineering professionals to assess these risks and criteria to lower these. This roadmap is intended to be a 'living document', which can be found on the SFPE website [2]. This paper provides peer developers with insights into the fire risk assessment tools, thus contributing to their future improvement.

Many engineering tools have been developed over the last decades to assist fire safety experts in assessing projects on criteria such as fire- and smoke development, the means of escape, and intervention. By substituting prescriptive-based design because of the introduction of sustainable building concepts new tools are needed [3]. These have become essential within the performance-based design process. In most cases to describe the necessary functional and operative requirements [4].

A fire risk assessment can be conducted as one of the inputs of the decision-making process to compare design options and to ensure that the residual risk is 'as low as reasonably practicable' (ALARP). But this all depends on the reliability of the applied risk assessment tool, and thus also calls for the development and introduction of new tools that will lead to more certain predictions, such as the effects on performance of changes in building materials, compartmentation, all kind of systems integrated, and fires leading to a total loss, including the social impact [5]. Currently, prescriptive-based requirements alone cannot be used as a reference for assessing buildings with unique functions and/or complex designs. And, these requirements seem to be often overvalued, so meeting them induces higher costs [6]. On the other hand, performance-based fire safety requirements are often based on equivalence with building legislation rather than on the benefits of avoided damage. In many cases, a fire safety engineer compares the level of fire safety with the level of safety when the building meets the building code requirements [7]. The real impact of choices based on a societal cost-benefit analysis (CBA) is, in most cases, not assessed. Therefore, new risk assessment tools should encompass more factors and data than solely technical ones. For instance, a CBA should become integrated [8] as well as social and political aspects of risk perception and respective

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tolerability [9].

Therefore, this paper addresses the following research question: Which fire risk assessment tools have been developed and have the potential to reliably predict the expected consequences of a fire, and what are their features, attributes, and limitations? We first conducted a literature review to identify fire risk assessment approaches with their related attributes and features according to which a building can be assessed. These attributes entail, for example, the behavior of occupants in a building and provide information about its variables. The interaction of attributes is well described by, amongst others [10], and [11]. A feature refers to a distinctive functionality of the tool, for example the way the output is displayed. Secondly, a survey (N = 42) was conducted to validate the findings from the literature review, and to derive more information. We found 26 fire risk assessment tools, which to some extent can predict the consequences of a fire. This study aims to provide an overview of a range of fire risk assessment tools, acknowledging their diverse nature and complexity. This study does not substantiate that the quantity of attributes always equates to a better tool. It highlights a range of attributes that could be relevant in various contexts. This means that the percentage scores given in this paper do not represent the quality of the tool, only the number of attributes checked by the respondents. We acknowledge that a tool with a focused, limited set of attributes may be more effective and appropriate for certain specific applications. The variety and scope of the tools we discuss cover a broad spectrum, so that we can only compare the number of fire consequence-related attributes.

This paper provides 12 contributing factors to assess fire risk assessment tools, for instance, validation, user-friendliness, and user functions which can be assessed. One of these, the 'fire consequence' contributing factor is divided into 10 sub-classes to assess all fire-related consequences, for instance, fire location, persons present, and applied measures. When the overall % score of the covered attributes is known in the public domain, competitors will challenge each other, which will lead to a greater number of tools, and subsequently, the refinement of existing ones with enhanced predictability of the potential consequences of fire incidents. Following upon, recommendations for the development of adequate tools are presented in the conclusion part of this paper.

2. Materials and methods

2.1. Literature review

The literature review entails fire risk assessment approaches mentioned in (peer reviewed and grey literature) papers and reports found with database searching. This search was complemented by using the reference lists of four relevant studies resulting in 333 academic papers. (1) Proposals for the development of a calculation model, Economic Impact of Fire [12], (2) Lloyd's Register Foundation's research project by Ref. [13], and of two theses of master students which were supervised by the first author of this underlying paper, (3) [14], and (4) [15].

After the first step of database searching (Fig. 1), the literature review itself was conducted by using the search engine Research Rabbit (RR) [16]. We started by identifying papers that had one or more of the following keywords in their title and/or abstract: fire; risk assessment; tool; software; simulator; model; framework; template; method; compu. One of the features of RR is the automatic search functions 'Similar Work',' Earlier Work', and 'Later Work'. Papers that include the aforementioned keywords were collected and resulted after the third step in 197 papers. And because the word 'index' occurs 54 times in the title and/or the abstract of these 197 papers, this keyword was added to the search criteria in the fourth step, resulting in 175 papers. Through these four steps many papers were excluded based on formulated criteria as illustrated in Fig. 1. For instance, a paper was deemed too specific when it detailed fire and/or smoke models. Too general, refers to papers in which a comparison is made between several tools.

After assessing all papers' titles and abstracts for eligibility as a potential fire risk assessment approach, 60 papers remained resulting in 44 fire risk assessment approaches. Two approaches were added to this list based on survey responses. Lastly, five risk assessment approaches were found in Ref. [17], one in Ref. [9], one in Ref. [18], and one in Ref. [19], chapter 75 'BFSEM Building Fire Safety Engineering Method', which also includes information about FIRE-RISK (formerly known as CESARE-Risk). As shown in Fig. 1, in total; 72 papers were identified in which 54 different fire risk assessment approaches were found as a starting point for an in-depth survey among the developers. Some papers refer to the same approaches. Fig. 1 provides a graphic illustration oversight of all criteria and the entire literature search and findings.

2.2. Survey design

The survey's goal was to gain peer insights of the literature review's identified list of existing fire risk assessment tools, and to score these tools on the number of fire consequence-related attributes. Ten subfactors are introduced in section 3.3.10 to score the tools.

The survey was drawn up using the Qualtrics software [20]. To receive as many responses as possible, most questions were asked so that all kinds of fire risk assessment approaches could be surveyed, from 'under development', 'developed for a small group' to 'operational tool'. For convenience, all approaches hereafters are called 'tools'. For several questions, the opportunity was also given to submit comments and/or add 'Other(s)' if applicable.

The survey consists of three sections of questions:

A. Questions about factual information regarding the development of the tool; i.e. tool introduction, technical specifications, stakeholders' involvement, and tool availability.
B. Information about the application(s) of the fire risk assessment tool; i.e. tool features, the field of application, tool characteristics and related attributes.
C. General questions; i.e. several questions with open textboxes for respondents to leave comments, a question about stakeholders' interest, and finally if the respondent gives permission to use their information in a publication.

Lastly, all responses and information derived from the survey have been anonymized. The survey questions can be requested from the corresponding author of this paper. Moreover, an overview of 54 fire risk assessment approaches found in 72 academic papers including a 'short description' and their references, can also be received upon single request.

2.3. Set-up

The survey starts with questions about the involved stakeholders. For tool acceptability it is of interest to know how many stakeholder groups are involved in the developing phase of a specific tool. It is thus important to know what stakeholder groups the intended tool users are, the most frequent users, what stakeholders would have an advantage when using the tool and which of the stakeholders are within their field of activities or professional network.

The survey consisted of several factors to test to what extent a fire assessment tool has the ability to assess the fire safety of a building. The following 12 factors were found in academic literature and available tool manuals: (1) tool validation, (2) tool costs and number of users, (3) user friendliness and support, (4) assessment guidelines the tool is based on, (5) integrated risk approaches, (6) integrated economic approaches, (7) costs of safety measures included, (8) user functions that can be assessed, (9) type of buildings that can be assessed, (10) programming language, tool category, and tool perspective, (11) integrated probability distributions, and finally, (12) their individual contribution to the assessment of fire consequences.

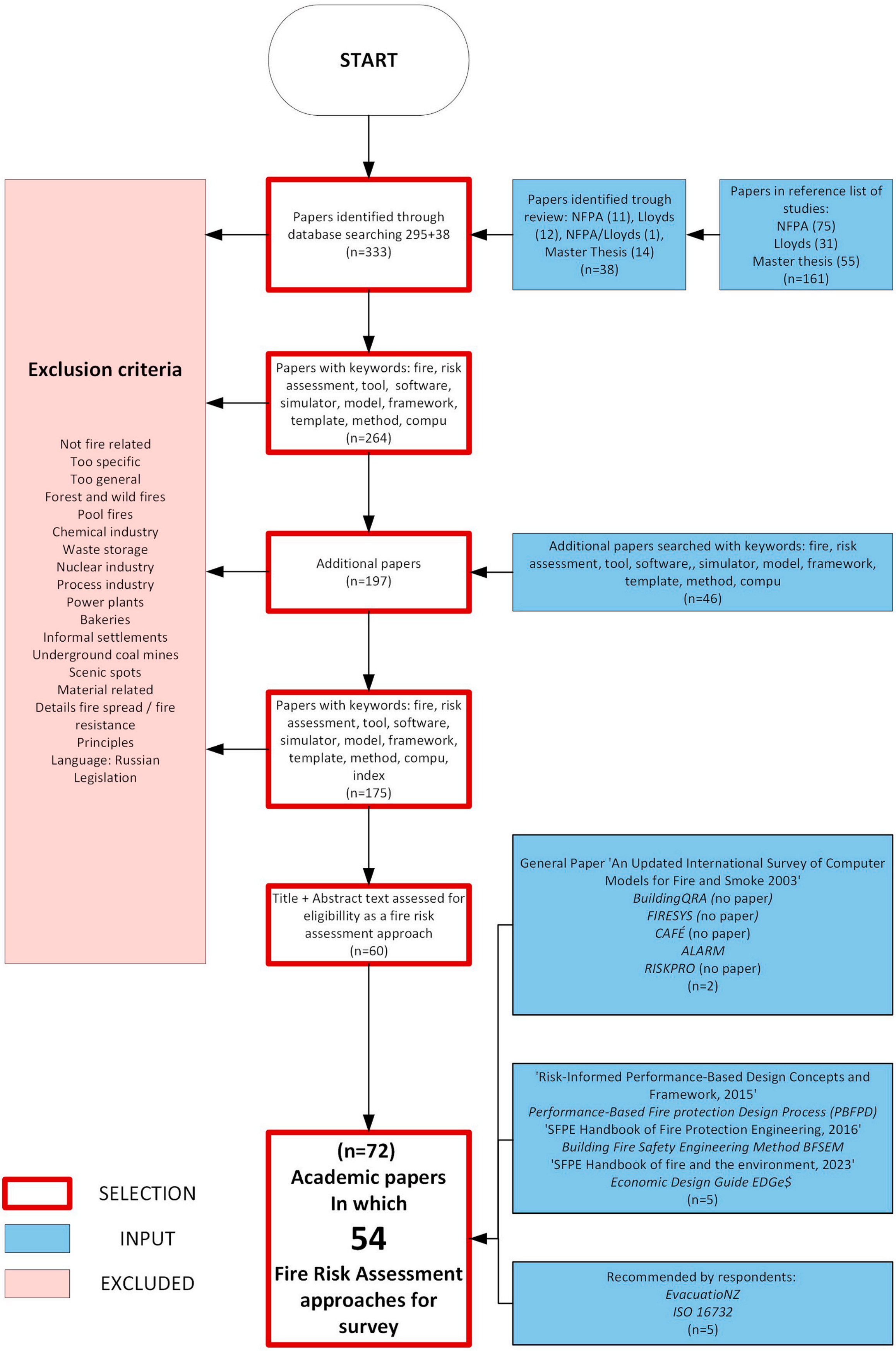

Fig. 1. Overview of the conducted literature study.

To structure the attributes, a distinction is made in the survey between the following six characteristics: [building-, people-, fire and smoke-, intervention-, environmental- and economic characteristics]. According to Ref. [21], Fire, Human, and Building are the three characteristics that determine the degree of fire response performance of occupants in the event of a fire in a building. This was also described in Ref. [22], as moving to a safe surrounding environment depending on the interaction between the building design, the conditions such as smoke, procedural aspects, and human behavior [23,24]. The fourth characteristic 'Intervention' was added by Ref. [25]. According to the [26], providing a fire-safe escape is the main objective. Existing building legislation does not take account of damage to the environment in case of fire which effects the overall sustainability of a building [27]. Also, business continuity and property loss are not considered. We therefore supplanted the characteristic scheme with 'Environment' and 'Economy', bringing the total of considered characteristics to six.

The survey's target audience are developers of fire risk assessment approaches. Therefore, from the papers found suitable for this study (section 2.1), we identified 42 email addresses from the respective papers' authors and/or developers. To these, the survey was sent out too.

Between September 19 and December 11, 2022, in total 172 first emails and follow-ups were sent to 42 developers and/or users worldwide whose addresses could be traced from the literature review. Eventually, this resulted in 26 responses. Additional sources, such as referred papers, were consulted to find out what attributes and features are included in fire risk assessment tools. Concerning CRISP, information was derived from Ref. [28], and from a technical description received from a respondent.

3. Results

On the question, "Were, or are you still, involved in the developer's process", an involvement of 18 respondents was observed. Most tools (N = 21) are used for education and research whereof 10 tools are used for commercial purposes. 4 tools are used for commercial purposes only. First, section 3.1 describes to what extent the prime stakeholders accept and apply fire risk assessment tools. Then, section 3.2 elaborates on tool availability, and section 3.3 concerns tools' contribution to fire risk assessment.

3.1. Stakeholders' involvement

When an assessment is conducted, the level of stakeholders' involvement and their number will influence the outcome. Therefore, a high number of stakeholder groups involved within the developers' domain of activities prior to and/or after the tool is developed ensures better adoption with clear goals and a transparent assessment process. Mostly the involved stakeholders have a different risk perception and their position within the fire risk decision process and corresponding responsibilities is sometimes not defined. When the division of responsibilities is not well organized, several gaps will arise resulting in unnecessarily high societal costs in case of a fire.

This section provides an overview of some general results about the stakeholders' involvement, and the usage of the twenty-four tools.

The following questions were asked:

- Who are the intended users or who are the target audiences.
- Who are the most frequent users of the tool? (ranked between 0 and 6) To enable comparing, the number was multiplied by 5/6.
- Which of the stakeholders have an advantage when using your tool? (ranked in order of importance between 0 and 5)
- Which of the following stakeholders is within your domain of activities? (ranked in order of importance between 0 and 5)

Stakeholder involvement in the early stage of the development of a risk assessment tool will lead to a more balanced fire safety approach and will therefore contribute to fire safety of the built environment and to a safer society. This first bar chart, Fig. 2, shows the 12 stakeholder groups whereby each of the twenty-four respondents was asked to check the four categories: intended users, frequent users, stakeholders' advantage, and developers' domain of activities. It is noticed that there are three clusters of stakeholders: (1) Knowledge cluster: University/Research, Fire consultant, and Fire service, (2) Financial cluster: Insurer, Bank, Real estate investor, Building owner, Private company, and (3) Regulatory cluster: Building code authority, Regulatory services/inspection, and Government. In general, we can see that the financial cluster is less involved.

Fig. 3 below illustrates the order of importance of each stakeholder according to the respondents. This aspect was only the subject of the three last questions [most frequent users, stakeholders having advantage and developers' domain of activities] where an answer could be given between 0 and 6 for the most frequent users based on their importance and between 0 and 5 for the other two questions. To compare the degree of importance (Y-axis), the total number concerning the most frequent users had to be multiplied by 5/6. This shows that from these two figures is that as an example, the University/Research stakeholder has an average score of 4.4 (=92.5 blue column Fig. 3 divided by 21 orange column Fig. 2) on a scale of 0–5, given by respondents who answered the question about the most frequent users. This high score is because 21 tools are for education and research use (See section 3.).

With one exception of the University/Research group, all respondents indicate that all individual stakeholder groups would benefit if fire risk assessment tools were applied (orange columns), compared to the current users (blue columns). Fig. 3 shows that in the same cases, more stakeholders are within their domain of activities (grey columns), compared to their most frequent users. An essential reason for this gap is the limited familiarity of operational tools outside the academic domain.

3.2. Availability of fire risk assessment tools

Fig. 4 gives an overview of the 26 tools of which information is received from respondents. It includes the year of introduction and the year of last update. Indicated by the survey respondents. The BuildingQRA approach developed by Ref. [17], is combined with several other models and renamed as FiRE in 2022.

One of the first questions in the survey concerns the tool classification which can be classified as:

- Fire Risk Model Tool
- Fire Risk Index Tool
- No classification

Based on the literature review most fire risk assessment tools can be classified as Fire Risk Modelling; "*to predict, and design measures to minimize, both direct and indirect losses due to fire.*" which definition is derived from Ref. [29], or as Fire Risk Indexing; "*scoring hazard and other system attributes to produce a rapid and simple estimate of relative fire risk*", which definition is derived from Ref. [11]. Fig. 4 shows the 26 operational fire risk assessment tools divided into model- (green), index-based (orange), or not classified (black). Three of the respondents of the listed tools did not check the 'no classification box'. The IFC-tool information was found in the literature [30]. The ISO 16732 tool mentioned in the survey responses refers to an international standard that provides the conceptual basis for fire risk assessment by stating the principles underlying the quantification and interpretation of fire-related risk.

The fact that a tool is identified does not mean that it is still available. Some of them were developed years ago and some of them were not maintained. Acceptance and application of fire risk assessment tools is dependent on their availability. The above Fig. 4 shows us that only a few fire risk assessment tools were operational over the last four decades. For example, the year 2014 was the most productive year with in total 14 actual tools. It also demonstrates that over the last decade, 20

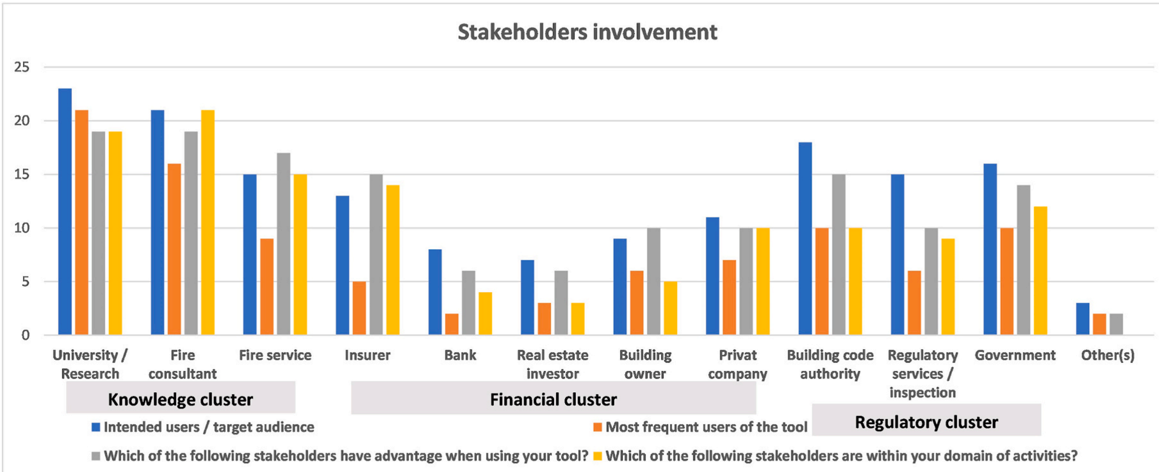

Fig. 2. Each stakeholder group divided into four categories (vertical axis = number checked by respondents).

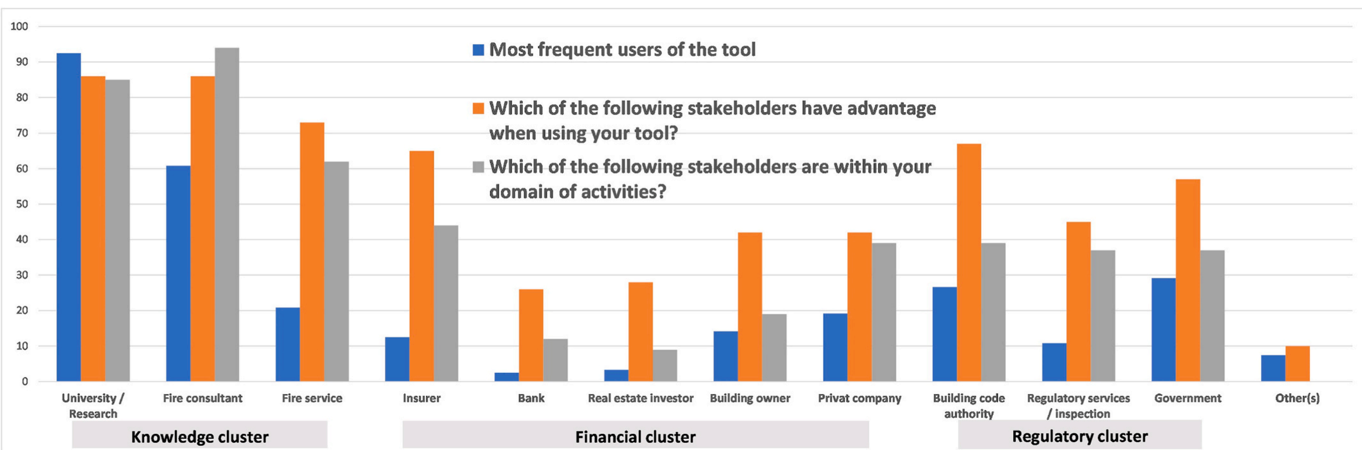

Fig. 3. Each stakeholder group is divided into three categories, each based on the order of importance according to the respondents.

tools were developed or have been updated and the remaining tools are outdated. This will not mean that we cannot learn from these tools. However, the prediction of the consequences will be more uncertain than the previous updated tools because of social trends and new building concepts as introduced in Section 1.

3.3. Fire risk assessment tools and their contribution to the twelve factors

The 12 contributing factors and related features and attributes are described in Sections 3.3.1 to 3.3.10. Special attention is paid to those attributes which to a certain degree are necessary to predict the expected consequences of a fire in terms of fatalities, property losses, business continuity, and/or social damage to neighbors and the environment. Because of this distinction, Sections 3.3.1 to 3.3.9 describe the factors from a more general point of view, instead of section 3.3.10 in which the tools are assessed on their individual contribution.

To assess the individual tools, reference is made to the Bow-tie structure which is originally developed within the oil and gas industry [31]. This is further elaborated in section 3.3.10. This section introduces the Bow-tie structure. The purpose of conducting a fire risk assessment is to evaluate the potential consequences of a high-risk activity (=an event caused by a hazard) based on the likelihoods of related threats and the effect of control measures. If the consequences can be predicted, an optimal choice can be made in the design stage between control measures (barriers) that either reduce the likelihood on the left side or mitigate the consequences on the right side (Fig. 5).

A Bow-tie consists of a fire event in the center, triggered by a hazard that may consist of a high-risk activity. The left side is the pre-event, where the preventive or proactive control measures are located to mitigate the likelihood prior to the first event. This is the so-called 'fault tree' where the possibility increases after every not working control measure. And at the right is the post-event, the so-called 'event tree' where the repressive or reactive control measures are located to mitigate the severity of the fire consequences. Measures are in this method called barriers and are divided into technical and non-technical, which in turn can be activated directly or indirectly. For instance, maintenance does not activate a barrier but will influence reliability in an indirect way.

3.3.1. Validation (factor 1)

Almost all tools (N = 18) are published in journals, of which in sixteen cases some kind of validation has been conducted, either by peers, by case studies, or both. Two out of the eighteen tools [FIER-Asystem, and FIRE-RISK] were not validated but only finalized with case studies. For the tools FiRE and Yaahp, no scientific papers were published. Four tools [CUrisk, FRIM, FiRE, and PBFPD] are still in the testing phase. Nine tools [AAMKS, EvacuatioNZ, F.L.A.M.E., FiRE, FRAME, ISO 16732-tool, Pathfinder, Pyrosim, and RISKCURVES] have been continuously improved over the last years.

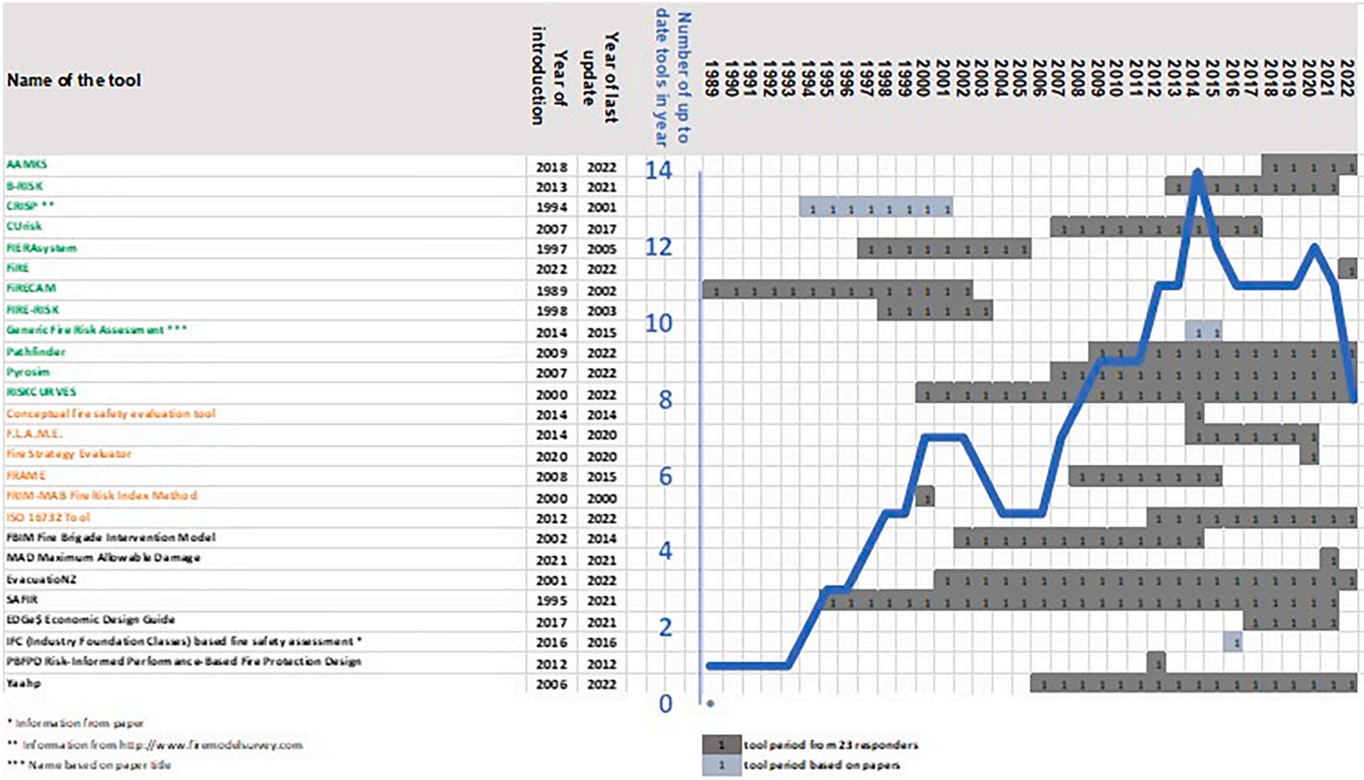

Fig. 4. The number of up-to-date fire risk assessment tools in each year (1989–2022) model- (N = 12, green), index based (N = 6, orange), or not classified (N = 8, black).

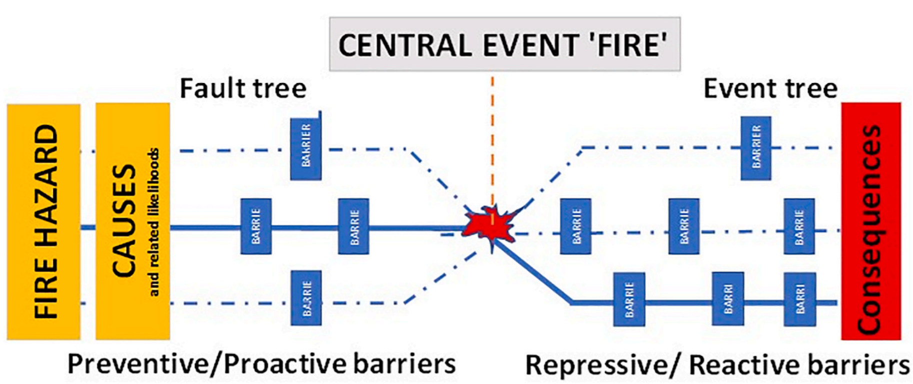

Fig. 5. The Bow-tie structure (figure by author).

3.3.2. *Costs and number of users (factor 2)*

Eight tools are free of charge and seven tools are not publicly available. A free trial version is available for the two tools developed by Thunderhead Engineering, Pathfinder and Pyrosim. The 'Fire Strategy Evaluator' respondent did not check any of these boxes but mentioned: "*There is exactly no software, only a calculation methodology*". The six respondents who included their prices show a significant difference. Four are around €250 to €1,000, one depending on academic use for €1500 or commercial use for €8,000, and one for €25,000 for a period of three years.

Two of the survey questions are about the number of users. Six tools have less than 100 users and five have more than 1000 users. Four tools within between. For all other tools, the respondents do not know or did not mention.

3.3.3. *Use friendliness and support (factor 3)*

One factor that influences the application of a fire risk assessment tool is its user-friendliness. Fig. 6 shows the more operational easy-to-use tool features, such as a timescale with essential characteristics, several 2D or 3D visualizations, tables, and graphs. It is worth mentioning that most respondents of model-, and non-classified tools checked one of the following features: timescale, visualization, tables and/or graphs. What stands out is that the interaction between tool functions in 75 % (18 out of 24) of the tools runs automatically. Fig. 7 shows the provided instruction materials, if limitations or disadvantages are described and the availability of assessor education and a user guide or manual. Five of the 24 respondents informed us that their source code is available.

If the box 'Other(s)' was checked by respondents, the open text boxes were used to describe additional features which are mentioned hereafter. The relative total fire risk assessment level, expressed as an index, value or a score, and the intervention or failure time. But also remarks regarding the safety margin, defined as the difference between performance estimate minus acceptance criteria. The agent locations,

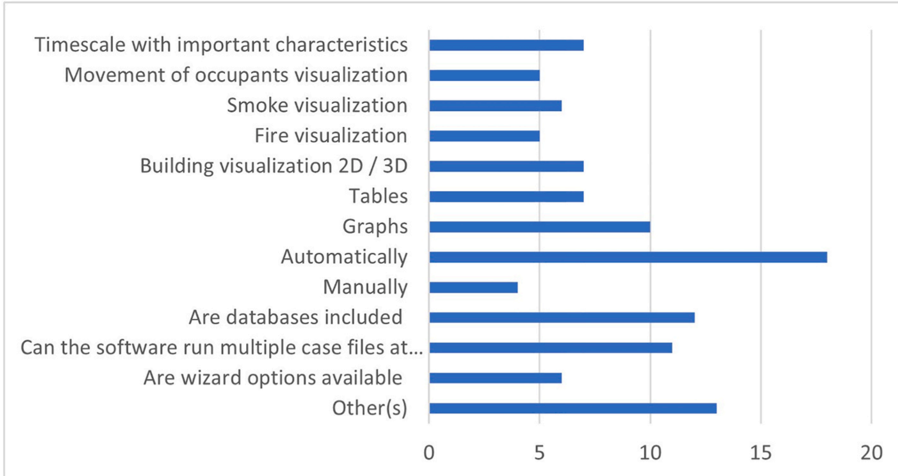

Fig. 6. User-friendliness (Operational-easy to use) 24 respondents.

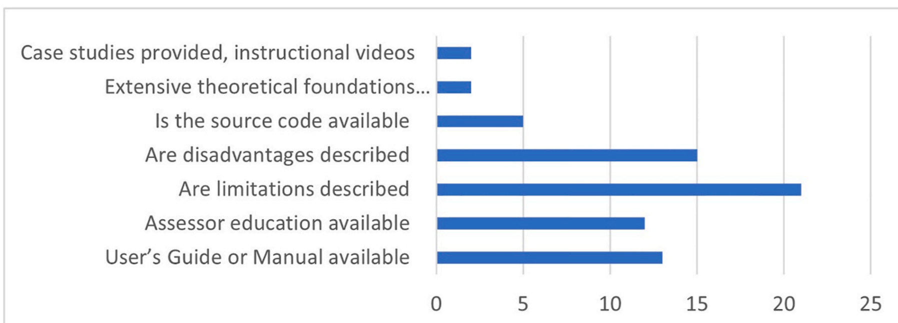

Fig. 7. User-friendliness (Instruction materials) 24 respondents.

decisions as a function of time, all kinds of generated data such as temperature, deformation, stresses, and the distances to heat/explosion/toxic levels.

3.3.4. *Assessment guidelines (factor 4)*

Choosing the best guideline for developing a fire risk assessment is important and depends on the assessment's purpose. An evaluation of risk assessment guidelines has been done by Ref. [32]. Table 1 shows that the SFPE Engineering Guide is mostly referred to, followed by the Published Document PD 7974. For six tools, no reference is made to any of these guidance documents. Five tools, [FIERAsystem, F.L.A.M.E., Fire Strategy Evaluator, MAD, PBFPD], refer to three or more guidance documents. For more information, see the Appendix.

3.3.5. *Safety approaches (factor 5 and 6)*

The two main categories of safety approaches which are checked by respondents are risk-, and economic approaches. See Tables 2 and 3. It is interesting to note that the event tree approach is included in nine tools, whilst the fault tree approach is only included in two of these nine tools. These two tools are the FiRE-, and MAD Maximum Allowable Damage

Table 1
References to fire risk assessment guidance documents, top 3 of 12.

Guidance Documents for Fire Risk Assessment	N = , out of 26 tools
SFPE Engineering Guide: Fire Risk Assessment	9
PD 7974-7:2019 Application of fire safety engineering principles to the design of buildings. Probabilistic risk assessment (+A1:2021)	7
ISO 16732-1:2012 Fire Safety Engineering	5

Table 2
Risk approaches, top 3 of 38 *(Factor 5)*.

Risk approaches	N = , out of 26 tools
Monte Carlo method	10
Event tree	9
QRA Quantitative Risk Assessment	8

Table 3
Economic approaches, top 3 of 17 *(Factor 6)*.

Economic approaches	N = , out of 26 tools
Cost-benefit analysis	6
Cost-effectiveness analysis	5
Value of statistical life[a]	5

[a] Two added because the respondents of AAMKS and CUrisk checked this box in the 'Economic characteristic' section of the survey.

tool. The Monte Carlo method is not included in any of the index tools. For the total list see the Appendix.

The following tools have included five or more risk approaches: AAMKS (N = 5), CUrisk (N = 5), FiRE (N = 9), Generic Fire Risk Assessment (N = 9), Pyrosim (N = 5), RISKCURVES (N = 7), Conceptual fire safety evaluation tool (N = 6), F.L.A.M.E. (N = 8), and MAD (N = 7).

Within this part of risk approaches a sub-category of engineering software such as FDS, CFAST, and Ozone are applicable for detailed assessing of fire and/or smoke phenomena. The following tools have included one or more of these engineering software: AAMKS (N = 1), Generic Fire Risk Assessment (N = 2), Pathfinder (N = 2), Pyrosim (N =

2), RISKCURVES (N = 1), Fire Strategy Evaluator (N = 1), MAD (N = 3), and SAFIR (N = 1). For more information see Table 2a of the Appendix.

To calculate the financial burden of the undesired fire consequences an interesting part of the available risk approaches is the economic-related attributes. None of the economic approaches were checked by respondents of index tools. The not classified tool 'EDGe$' contains 7 of a total of 17 economic approaches. Because the respondent only checked the boxes 'Various financial indicators' box, and 'Economic analysis', the following were added after going through the 'Economic Decision Guide Software (EDGe$) Tool: User Guidance' [33],: NPV Netto Present Value, ROI Return On Investment, IRR Internal Rate of Return, BCR Benefit Cost Ratio, Non-Disaster ROI, and finally, the Value of statistical life. For the total list see the Appendix.

The following tools have included three or more economic approaches: CUrisk (N = 4), FiRE (N = 5), Generic Fire Risk Assessment (N = 7), and EDGe$ Economic Design Guide (N = 7).

3.3.6. Costs of safety measures (factor 7)

The respondent of the FRAME index tool checked only the 'replacement costs' as listed in Table 4. All other 'Costs of safety measures' were checked by the respondents of model tools. For the total list see the Appendix (see Table 4).

3.3.7. Type of buildings and user functions (factor 8 and 9)

To find out which tool is suitable for what type of building several distinctions must be made between: residential and non-residential buildings; the different user-functions of buildings such as for residential, industrial, or office use; and the situation of the building for example when it is under renovation or refurbishment and still in use (see Tables 5 and 6). Renovation or refurbishment during use requires more attention concerning the consequences of fire than when the building is not in use. The fire scenario depends on the fast-changing activities in the building which will lead to changing barrier quality, especially when it comes to renovation and buildings that are under construction [34].

Buildings with a public function typically housed people who are unfamiliar with the building layout. This influences their responses to fire occurrence, and their awareness as to how a fire can propagate. Therefore in such situations the management delivery system necessarily takes on a larger part of the responsibility to compensate for users' potential incapacity to respond to fire occurrence in the given context.

In the case of other user functions the open text boxes mention: (1) large spaces (FIERAsystem), (2) or that it is theoretically applicable for all types of buildings (Generic Fire Risk Assessment), (3) it is a compartment fire model, requiring user to input data appropriate for the occupancy (B-RISK), (4) risk assessment based on lethality or damage (heat load) criteria: presenting Individual risk, societal risk and consequence risk criteria. (RISKCURVES).

About the type of buildings, no information is available for two of the 26 tools [CRISP, PBFPD]. No information is available concerning user functions of six of the 26 tools [CRISP, PBFPD, FBIM, IFC, Fire Strategy Evaluator, Yaahp].

3.3.8. Programming language, tool category, and tool perspective (factor 10)

In total twenty-two respondents filled in the tool programming language. In summary, it means the following distribution: Java-C++ (N = 7), Visual Basic (N = 6), EXCEL (N = 3), FORTRAN (N = 2), Python (N = 2), Matlab (N = 1), and Delphi (N = 1).

Table 4
Costs of safety measures, top 3 of 7.

Costs of safety measures	N = , out of 26 tools
(Building) Costs passive safety measures	**7**
(Building) Costs active safety measures	**7**
Maintenance costs	**6**

Table 5
User functions (N = 11) *(Factor 8)*.

User functions	N = , out of 26 tools
Residential	18
Office	16
Hotel	15
Industry	14
Shop	14
Meeting	13
Healthcare	13
Education	13
Prison	12
Sports	11
Other(s)	4

The tool category was analyzed [qualitative, semi-qualitative, quantitative]. In total 83 % of the models, 17 % of the index tools, and 75 % of no classification are quantitative. 83 % Of the index tools are semi qualitative. The tool perspective, static or dynamic, in total 50 % (7 out of 14) of the quantitative tools are dynamic and time dependent. Six quantitative tool respondents did not check this box. And only one quantitative tool is static. Instead of 50 % (3 out of 6) of the semi qualitative tools are static and not time dependent. Of which three respondents did not check this box.

3.3.9. Probability distribution (factor 11)

Because of limited data and the lack of reliable data, we include probability distributions in our calculations. How to treat probability depends on the limitations of the information and data provided by involved stakeholders. Uncertainty can be translated into a probability of distribution (see Table 7).

Table 7, provides an overview of the number of boxes checked by respondents, including added 'Others'. If the box 'Other(s) was checked, three respondents added the below sentence to the textbox. (1) MAD Maximum Allowable Damage: "*It focuses on understanding the largest consequences of the fire safety design and then establishes it as a design limit. Nevertheless, these consequences can be expressed as a distribution (any), rather than a discrete answer.*" (2) RISKCURVES: "*QRA involves multiple scenario's, each having a failure frequency, corrected with weather statistics (wind direction/Pasquill classes).*" (3) FIRE-RISK: "*Depends on the quality of the data.*"

A distinction is made between the classification's 'index', 'model', and 'no classification'. It shows that index-tools do not include a kind of probability distribution. About the CRISP model tool, no information is available. Ten out of 12 of the surveyed model tools have included the normal distribution. Of the non-classified tools, the EvacuatioNZ- and EDGe$ tool are the only ones which have several probability distributions implemented.

The application of the types of probability distribution depends on the attribute and the related dataset. The Gaussian or so-called normal distribution is the most common type of probability distribution. The survey outcome shows a variety of distributions that are included in several tools. Which of the distribution is applicable is dependent on the attribute to be assessed. For example, you can use the discrete-distribution for occupants' change behaviour, the triangle-distribution

Table 6
Type of buildings (N = 6) *(Factor 9)*.

Type of buildings	N = , out of 26 tools
Design	21
Existing: in use	20
During renovation: in use	14
Under construction: not in use	11
During renovation: not in use	9
Other(s) such as: vulnerability assessment, problem solving	3

Table 7
Probability distributions top 3 of 18.

Probability Distribution	N = , out of 26 tools
Normal	12
Lognormal	7
Discrete	7

for the heat release rate, and the pareto-distribution for the fire size. Beta and Student-t are not mentioned as a probability distribution. And eleven tools, do not include a probability distribution at all. For more information see the Appendix.

3.3.10. Contribution to the assessment of fire consequences: introduction of the Bow-tie framework (factor 12)

To predict the consequences of a fire, all kinds of attributes of the built environment, the use, and the fire phenomenon itself must be clearly understood. For example, the number of occupants in the building and their ability to flee, the place where the fire starts, the structure, the fire load, or the fire service response. These factors will help users to select a tool depending on their needs and considerations. As described in the introduction section, the purpose of a fire risk assessment tool is to in some extent predict the consequences of a fire. All hereafter-listed attributes are taken from the six characteristics of section 2.3 and are divided into 10 sub-factors. Only the 'costs of safety measures' attributes are taken out because they do not influence the assessment outcome.

The paper adopts the Bow-tie structure (see Fig. 5) as an underlying framework for classifying the attributes on the cause, consequence, and barrier side (as shown in Table 8). This aims to draw meaningful conclusions concerning the overall tool's ability to assess the fire safety of a building. The consequences graphic (Fig. 8) is introduced which visualizes the following three main questions as described by Kaplan and Garrick (1981): (1) What can go wrong, (2) what is the likelihood of that event, and (3) what are the consequences? Besides these three questions, a fourth question was added which is: (4) How do you feel about it? The latter feeds the discussion on the decision maker's preferences regarding the probable risk. Because "*without preferences, the decision maker doesn't care what happens there is no risk*" [35]. To visualize the decision maker's preferences, Fig. 8 shows as an example of two upward going curves to illustrate the case of barriers not failing and thus resulting in fewer fire consequences.

All sub-factors (N = 10) from Table 8, which include the related attributes that could be checked by respondents, are linked to either the

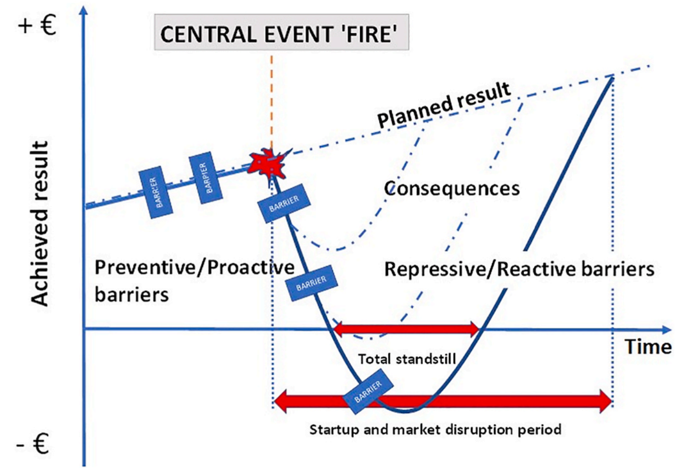

Fig. 8. Consequences graphic adapted from [36].

left, the middle, or the right side of the fire event. 'Other(s)', gave the respondents the opportunity to add an attribute or place their comments in the text box. Analyzing the 'Other(s)' checkboxes shows the different opinions of respondents. That means that no same comments were made by multiple respondents. When the respondents did not add anything substantive in the open text box, these were not included in the table.

Several sub-factors from Table 8 are described below.

A fire scenario is represented by the center event of the Bow-tie framework and therefore the right side consists of reactive or repressive safety measures to mitigate the severity of the fire consequences. According to ISO 13943 Fire Safety-Vocabulary (2017), a fire scenario is defined as a "*qualitative description of the course of a fire with respect to time, identifying key elements that characterize the studied fire and differentiate it from other possible fires*" [38]. A fire scenario defines the process from ignition to a fully developed fire, until the decay phase. Also, the impact on the environment and all kinds of systems are related to the fire scenario. For describing the location of ignition, as a minimum, one of the three questions about the 'Fire location', [Indoor, Outdoor, Construction] must be checked by the respondent.

Fig. 9a and b give an overview of the sub-factors (N = 10) and related attributes.

In total 14 of the 26 tools can only assess a fire of which the development starts indoor. The model tools Pyrosim and Pathfinder can also assess a fire which starts outdoors, and a fire of which the development

Table 8
Bow-tie framework with sub-factors (N = 10), and related number of attributes (N = .).

	Sub-factors (event)	**N=**	
	Fire location	**3**	
	Fire development	**4**	
Sub-factor (left side)	**N=**	**Sub-factors (right side)**	**N=**
Preventive barriers	2	Repressive barriers	26
		Persons present	5
		Evacuation	5
		Fire and smoke	15
		Consequences	25
Sub-factor: Uncertainty 14			
Sub-factor: Management delivery system 4			

The trustworthiness of the applied safety measures/barriers can be (partly) traced back to the management delivery system. In other words, it will influence the uncertainty of safety barriers, and indirectly all other sub-factors. According to Ref. [37], attributes such as 'functionality/effectiveness, reliability/availability, response time, robustness, and finally a description of the triggering event or condition' are also needed to describe the performance of safety measures (risk mitigation/barriers).

Name	AAMKS	B-RISK	CRISP **	CUrisk	FIERAsystem	FIRE	FIRECAM	FIRE-RISK	Generic Fire Risk Assessment ***	Pathfinder	Pyrosim	RISKCURVES	Conceptual fire safety evaluation tool	F.L.A.M.E.	Fire Strategy Evaluator	FRAME	FRIM-MAB Fire Risk Index Method	ISO 16732 Tool	EDGe$ Economic Design Guide	EvacuationNZ	FBIM Fire Brigade Intervention Model	IFC (Industry Foundation Classes) fire safety assessment *	MAD Maximum Allowable Damage	PBFPD Risk-Informed Performance-Based	SAFIR	Yaahp	Total score
Fire location (N=3)																											
Fire location: indoor	1	1		1	1	1	1	1	1	1	1		1		1	1		1									14
Fire location: construction										1	1		1	1				1									5
Fire location: outdoor										1	1							1									3
Fire development (N=4)																											
Fully developed	1	1		1		1	1	1	1	1	1		1					1									11
Growth	1	1		1		1	1	1	1	1	1							1									10
Ignition	1	1		1		1	1	1	1	1	1							1									10
Smoldering						1	1	1	1		1							1									6
Preventive barriers (N=2)																											
Level of inherent safety						1							1										1				3
Level of resilience						1							1										1				3
Repressive barriers (N=26)																											
Active fire safety measurements	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1		1			1				19
Passive fire safety measurements	1	1		1	1	1	1	1	1		1		1	1	1	1	1	1				1	1		1		18
Smoke detection	1	1	1		1	1	1	1	1	1	1				1	1	1			1							14
Fire detection	1	1		1	1	1	1	1		1	1			1	1	1	1			1							14
Fire protection	1	1		1	1	1	1	1	1		1			1	1	1	1								1		14
Compartmentation	1	1	1		1	1		1		1	1		1			1	1	1					1		1		14
Egress	1		1		1	1		1		1	1		1			1	1	1		1		1	1				14
Sprinkler	1	1		1	1	1	1	1	1		1			1	1	1	1										13
Fire resistance of building components		1		1	1	1	1	1	1		1			1	1	1	1										12
Internal / automatic fire suppression	1	1		1	1	1	1	1	1					1	1	1											11
Smoke control	1	1		1	1	1	1	1		1	1				1		1										11
Fire service response	1			1	1		1	1	1					1	1	1					1						10
Alarm Sound signal	1				1	1	1	1	1					1	1					1							9
Smoke exhaust	1	1				1		1		1	1				1	1	1										9
Fire endurance of structural elements		1		1		1	1		1		1				1		1								1		9
Automatic fire department call-up	1			1	1		1		1						1	1					1						8
Alarm Voice communication	1				1	1	1	1						1	1					1							8
Smoke resistance of building components	1	1				1	1		1						1	1	1										8
Pressurization					1		1	1		1	1				1												6
Smoke dampers	1						1			1	1				1		1										6
Manual fire department call-up					1				1						1	1					1						5
Internal / manual fire suppression	1							1	1					1		1											5
Fire dampers							1			1	1				1		1										5
Level of resilience						1							1										1				3
Human redundancy						1																					1
Water mist															1												1
Persons present (N=5)																											
Occupants number	1		1	1	1	1	1	1	1	1		1	1	1	1	1	1	1		1							17
Mix of both disabled or not disabled	1				1		1	1	1	1			1			1	1	1		1							11
Other(s): Be specified/Walking speeds/Presence factor				1		1						1															3
Number disabled														1													1
Other(s): Distribution, daytime/nighttime, inside/outside												1															1
Evacuation (N=5)																											
Occupant evacuation	1		1	1	1	1	1	1	1	1			1	1	1	1	1	1		1		1					17
Occupant response	1			1	1	1	1	1	1	1				1	1	1		1		1							13
Human behavior	1			1		1	1	1		1				1	1			1		1							10
Distinction between: Awake, asleep	1			1		1		1						1	1	1				1							8
Other(s): Premovement times						1																					1

Fig. 9a. Overview of sub-factors [fire location, fire development, preventive barriers, repressive barriers, persons present, evacuation] and related attributes.
*Information from paper.
**Information from http://www.firemodelsurvey.com and Technical description by Jeremy Fraser-Mitchell.
*** Name based on paper title.

Name	AAMKS	B-RISK	CRISP **	CUrisk	FIERAsystem	FIRE	FIRECAM	FIRE-RISK	Generic Fire Risk Assessment ***	Pathfinder	Pyrosim	RISKCURVES	Conceptual fire safety evaluation tool	F.L.A.M.E.	Fire Strategy Evaluator	FRAME	FRIM-MAB Fire Risk Index Method	ISO 16732 Tool	EDGe$ Economic Design Guide	EvacuatioNZ	FBIM Fire Brigade Intervention Model	IFC (Industry Foundation Classes) fire safety assessment *	MAD Maximum Allowable Damage	PBFPD Risk-Informed Performance-Based	SAFIR	Yaahp	Total score
Fire and smoke (N=15)																											
Fire propagation within the compartment	1	1		1	1	1	1	1	1	1	1				1	1							1				13
Smoke dispersion to adjacent compartments	1	1	1	1	1	1	1	1		1	1									1			1				12
Radiation	1	1		1	1	1	1	1		1	1	1											1				11
Concentration CO-CO2	1	1	1	1	1	1	1	1		1	1												1				11
Smoke dispersion within the compartment	1	1	1	1		1	1	1		1	1					1							1				11
Decay	1	1		1		1	1	1	1	1	1							1									10
Fire propagation to adjacent compartments		1		1	1	1	1	1	1	1	1												1				10
Soot	1	1		1		1	1			1	1	1											1				9
External conditions (wind, temperature etc)	1	1		1						1	1	1											1				7
Internal conditions (HVAC etc)	1	1						1		1	1												1				6
Domino effect internal and/or external fire spread (distance)						1					1																2
Other(s): Flame dimensions												1															1
Other(s): Stack effect and season temperature							1																				1
Melting / dripping																							1				1
Falling debris																							1				1
Fire consequences (N=25)																											
Expected number of deaths	1		1	1	1	1	1	1	1			1							1	1		1					12
Expected losses				1	1	1	1	1	1										1								7
Owners property loss	1			1		1	1		1							1											6
Costs fire and smoke				1	1	1	1	1															1				6
Expected number of injuries	1			1		1		1											1								5
Pollution by smoke										1	1	1			1												4
Expected downtime				1	1	1																					3
Owners business interruption				1		1		1																			3
Costs intervention				1			1																				2
Damage to the local environment											1																1
Damage to the adjacent property											1																1
Other(s): Smoke dilution due to weather conditions												1															1
Expected societal risk	1																										1
Required amount of fire extinguishing water																											0
Fire insurance administrative costs																											0
Value of donated time by volunteer fire fighters																											0
Fire-fighting organizations																											0
Damage to the local environment by debris																											0
Damage to the local environment by smoke																											0
Damage to the local environment by water																											0
Damage to infrastructure																											0
Damage to adjacent buildings																											0
Costs environment																											0
Pollution by debris																											0
Pollution by firewater																											0
Uncertainty (N=14)																											
Failure probabilities passive measures	1	1		1	1	1		1	1				1		1			1									10
Effectiveness active measures		1		1	1		1	1	1	1			1		1												9
Failure probabilities active measures	1	1		1	1	1		1	1						1			1									9
Effectiveness fire and smoke	1	1		1			1	1					1		1								1				8
Availability active measures	1	1				1	1	1	1				1	1													8
Effectiveness passive measures	1	1		1			1	1	1				1	1													8
Suppression effectiveness		1		1			1	1	1				1														6
Failure probabilities intervention	1	1		1		1			1									1									6
Availability intervention		1					1	1					1		1												5
Availability passive measures	1						1	1					1	1													5
Availability organizational measures								1					1		1												3
Failure probabilities organizational measures	1							1										1									3
Human failure rate						1									1												2
Effectiveness organizational measures								1					1														2
Management system (N=4)																											
Training	1												1	1	1	1											5
Maintenance								1						1	1		1										4
Monitoring														1	1												2
Enforcement														1													1

Fig. 9b. Overview of sub-factors [fire and smoke, fire consequences, uncertainty, management delivery system] and related attributes.

starts in the construction, such as the wall or roof cavity. This is the same for the index tool 'ISO 16732-tool'. The conceptual fire safety evaluation index tool can assess a fire of which the development starts indoor and in the construction. None of the not classified tools have included this possibility. The same for the fire development, which is not checked by the respondents of not classified tools. Of the index tools, only one, the ISO 16732-tool, has included all four fire development phases. The Conceptual fire safety evaluation index tool has only included the fully developed fire phase. Nine model tools have included three or more fire development phases.

The preventive barriers' attributes, 'level of resilience' and 'inherent safety', are both checked by the respondents of the FiRE-, Conceptual fire safety evaluation-, and MAD Maximum Allowable Damage tool. Inherent safety is typically considered as a preventive control measure on the left side of the Bow-tie structure and is often applied in the design phase of a building to reduce, avoid, or eliminate hazardous activities and therefore decrease the likelihood of a fire event occurring. In contrast, the level of resilience is considered to be part of both sides of the Bow-tie structure. That brings the total number of 102 unique attributes to 103. A (brief) text which was included in the text box 'Other (s), has been included in Fig. 9a and b.

Environment and the societal consequences are in most cases not included as attributes in the available tools. There are no tools that include an assessment of the pollution by firewater, and/or the required amount of fire extinguishing water. Furthermore, the pollution by debris and damage to the local environment by water, smoke, or debris, is not included in the assessment. The same goes for the value of donated time by volunteer firefighters, and the fire insurance administrative costs. A crucial topic which is not covered in the surveyed tools is the damage to adjacent buildings and/or infrastructure. Only the Pyrosim model tool assesses the damage to the adjacent property, and to the local environment, which questions were asked in the 'output data' section of the survey. The reason that the topic, damage to adjacent buildings and/or infrastructure, was not checked is that this was asked within the 'economic characteristic' section of the survey which was not checked by this respondent.

Most index and model tools include uncertainty, while non-classified tools do not. Within the six characteristics-related survey questions the following uncertainty attributes could be checked by respondents: effectiveness, availability, and/or failure probability of the applied control measures. This was done for 4 of 6 (=67 %) of the index tools, and 9 of 12 (=75 %) of the model tools. Only the MAD tool respondent checked the fire and smoke 'effectiveness' box.

Uncertainty has a significant impact on what can be expected from safety measures in case a fire occurs. Across the entire breadth of the Bow-tie framework the 10 sub-factors and related attributes will influence the fire scenario. An important one is the trustworthiness (expected quality in terms of reliability and availability) or uncertainty of the applied operational barriers, which will be determined by the management delivery system, as described by Ref. [39]. Another reason to include uncertainty is the fact that fire safety measures (barriers) need to be controlled. As described by Ref. [40]: the management system; *'has a direct impact on the reliability and effectiveness of the barriers and, hence, the probability of the scenarios involved.'* According to Ref. [41], the quality of safety measures (barriers) is determined by seven attributes which all together give an indication of the trustworthiness. It is about *(1) effectiveness: the ability of a barrier to perform its necessary function correctly; (2) reliability: the likelihood that a barrier will be able to perform its necessary function, given the aforementioned conditions, for a specified period of time; (3) availability: the chance that a barrier will function at any point in time; (4) costs: the costs of keeping the barrier functional, reliable and available; (5) robustness: the ability to continue to function in the event of (extreme) environmental influences such as an incident; (6) response time: the time from activation of the barrier to the execution of the intended function; and finally (7) the "Trigger": the event or condition that activates the barrier.*

From the before mentioned aspects only (1) effectiveness, (2, 5) what can be put together as failure probability, (3) availability, and (4) costs were questioned in the survey. For the aspect 'costs', see 3.3.6.

The Bow-tie preventive side is less developed than the repressive side. Interesting to note is that as an outcome of the literature review and the fact that respondents did not add distinctive preventive safety measures, the left side of the Bow-tie is less exhaustive than the right side. According to Ref. [39]: *"it is needed to encourage the entire organization for a proactive, long-term commitment to improve safety culture. Communication about the advantages and importance of this proactivity and this commitment is key in this regard."* The more *'reactive focus'* is also mentioned in the report 'Chemische clusters en veiligheid - Drijfveren en hindernissen voor samenwerking' [42]. According to Ref. [40] training is a behavior related system provided by management. Monitoring and maintenance are part of the hardware related systems. Both are part of the management delivery system and in that regard will influence the trustworthiness of safety measures. Enforcement is also a behavior related system. For instance, compulsory training to get an operation license could be considered as one type of enforcement.

Preventive measures seem to receive less attention in FPE (fire protection engineering) literature relative to PSE (process safety engineering), [43]. In Ref. [44] there is also stated: *"Preventive building fire safety is managed mostly by the building owners. The choices made by these private decision-makers are, however, restricted by fire safety codes and regulations. The code provisions should thus be optimized at societal level based on the principles of monetary optimization and societal risk acceptance"*.

For identifying so called 'precursors' such as false alarms, which are situated on the prevention side of the Bow-tie, use can be made of the developed 7-stage protocol by Ref. [45].

4. Discussion and key findings

This section concerns fire risk assessment tools having the potential to make a reliable prediction of the expected consequences of a fire in terms of fatalities, property losses, business continuity, and/or social damage to neighbors and the environment.

4.1. Stakeholders' interest

The survey respondents could select the following stakeholders [University/research institutes/students, Fire consultant, Fire service, Insurer, Bank, Real estate investor, Building owner, Private company, Building code authority, Regulatory services/inspection, Government] and if one was missing they could be added in the text box 'other(s)'. Only five respondents used this text box. (1) To the question "who are the most frequent users of the tool", the following text box was added by the 'FIERAsystem' respondent: "*a collaboration between university/students, the building owner, and the government*". (2) To the question "which of the listed stakeholders have an advantage when using your tool", the following text box was added by the 'MAD Maximum Allowable Damage' tool respondent: "*occupants and those that could potentially be affected by a fire that exceeds the design limit*". (3) To the questions: "who are the intended users/target audience", and "which of the stakeholders have an advantage when using your tool", the following text box was added by the 'Conceptual fire safety evaluation tool' respondent: "*Architects, Structural-, Mechanical and Electrical engineers*". (4) To the question "who are the intended users/target audience", the following text box was added by the 'FiRECAM' respondent: "*Any government research organization*". And the last one, (5) to the question "who are the intended users/target audience", and "who are the most frequent users of the tool", the following text box was added by the 'RISKCURVES' respondent: "*Consultancy, Oil & Gas, Chemical Companies*".

The addition of two important stakeholder groups, 'Architects' and 'Engineers' were recommended by respondents. The stakeholder group 'Governmental research organization' is already part of the first one 'University/Research' and the oil & gas/chemical industry fall under the

'Private company' heading. The stakeholder 'Private company', also exists for all kind of subcontractors and suppliers which in many cases are not the owner of the building but only the owner of the building content. The stakeholder group of manufacturers of building products and installations was not added.

The question 'why should all these stakeholders be involved' is already partially answered in section 3.1. The main reason is that those stakeholders who take part in the design and construction process of a building must be well informed about all available tool attributes within their field of expertise. The level of interest can differ for each stakeholder. Until now this pallet of interest has not been well surveyed but will have a significant impact on the acceptance willingness because sometimes stakeholders have competing objectives.

4.2. Difference between index and model tools

Index and model tools can complement each other in such a way that the consequence output will be more accurate. After analyzing the survey answers we have observed that in most cases 'models' include more attributes. This means that in general fire risk assessment models can predict the consequences of a fire more accurately. But will it still be possible to predict the consequences within an acceptable margin of probability? According to Ref. [11] fire risk indexing can be beneficial in several situations: *"1. Where greater sophistication is not required. 2. Where risk screening will be cost-effective. 3. Where there is a need for risk communication."*

4.3. Difference between direct and indirect involved stakeholders

In section 3.1, it is noticed that there are three clusters of stakeholders: (1) Knowledge cluster: University/Research, Fire consultant, and Fire service, (2) Financial cluster: Insurer, Bank, Real estate investor, Building owner, Private company, and (3) Regulatory cluster: Building code authority, Regulatory services/inspection, and Government. Cluster 1, and 3, consist of the indirect stakeholders because they are not directly affected by the fire consequences. Contrary to cluster 2, which consists of the direct stakeholders.

Figs. 2 and 3, in section 3.1, demonstrate that several direct stakeholder groups in the middle of the chart are less often involved. To find out these differences, two of the stakeholder-related questions were analyzed. In short there are two stakeholder-groups: indirect stakeholders who are responsible for the fire safety of the built environment in general and must bear the societal, mostly indirect burden, and those who must bear the direct financial consequences caused by a fire and in most cases have no problem with high societal costs. In section 3.1, defined as the 'Financial cluster'. Fig. 10 shows the involvement of this cluster consisting of five stakeholder groups. 15 respondents out of 24 included one or more of these stakeholders. The other 9 respondents did

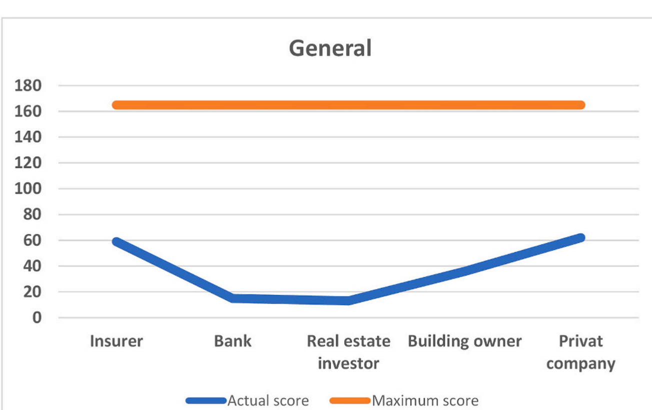

Fig. 10. Score of direct involved stakeholders.

not include any of these five stakeholders. [AAMKS, Conceptual fire safety evaluation tool, EvacuatioNZ, FBIM Fire Brigade Intervention Model, FiRE, FIRE-RISK, FRIM-MAB Fire Risk Index Method, PBFPD Risk-Informed Performance-Based Fire Protection Design, SAFIR].

For analyzing the financial cluster part (direct stakeholders) of Figs. 2 and 3, the score of the following two questions were added together. Question one, 'Most frequent users of the tool', a score between 1 and 6, and question two, 'Which of the following stakeholders are within your domain of activities', a score between 1 and 5. The maximum score which could be given is $15 \times (6 + 5) = 165$. The figure shows that the average score (22 %, distribution between 13 and 62) of this group of direct stakeholders is rather meager. The difference between model-, and index-tools is also analyzed. Model tools have an average score of 17.5 %, versus index tools 27 %. This means that regarding the index tools, the direct stakeholders are more involved, maybe because of its user-friendliness.

4.4. Tool availability, reliability, and limitations

In section 3.2 the availability of tools was analyzed, which shows that over the last decade, 20 tools (8 model, 5 index, 7 not classified) were developed or have been updated. The remaining tools are outdated. According to the respondents' answers, the CUrisk tool was last updated in 2017 versus AAMKS and FiRE in 2022. Unfortunately, AAMKS and FiRE have a very low stakeholders' involvement, whereby in the case of most frequent users and/or within their domain of activities, none of the direct stakeholders are checked by respondents. And both tools have respectively 10/100 users.

A low update frequency and underserved areas are not beneficial in this case. Because a well-applied probability distribution should cover all possible outcomes and small changes in the data should not result in significant changes in the probabilities. The usefulness of all found risk assessment tools is unclear, and there is a need for research to enhance them.

As described in the objective of this research, it is expected that a tool can predict the consequences of a fire to a certain degree of accuracy. In this section, the tools are analyzed for their ability to predict fire consequences. The prediction depends on the selected attributes in section 3.3.10, which were found in the literature. The first difference regarding the number of included tool attributes is between the two classifications and the not classified tools. In this section, a comparison of attributes is made by distinguishing between 10 sub-factors (Table 9: part A), of which each of them has an influence on the fire risk assessment generated prediction of the fire consequences. The attributes derived from Fig. 9a and b, are processed in the table below by the listing of the total number of attributes per sub-factor (B), and the % of attributes (C), which is differentiated between the three tool classes (D). In part E, the name of the tools which have the highest, and second highest number of attributes within a topic are mentioned.

The average score of the not classified tools is very low at 5.8 %. The table shows the difference between model-, index-, and not classified tools. In general, the model tools have a higher score than the index tools, with two exceptions where the index tools score significantly higher than the model tools. These two are the management delivery system (model 4%-index 42 %), and the preventive barriers (model 8%-index 17 %). This means that developers of the model tools probably can learn from the index tools developers.

Table 10 gives an overview of the surveyed tools. The average % of attributes included in the model tools is 36,1 % (Table 9), within a distribution between 52 % and 10 % (Table 10). The three tools in this class with the highest number of attributes are FIRE-RISK, FiRE, and AAMKS, which cover approximately 50 % of the in literature found attributes (Table 10). The average % of attributes included in the index tools is much lower (Table 9, 24,9 %), whereby only the Fire Strategy Evaluator covers 38 % of all attributes. All the others in this class are between 25 % and 18 % (Table 10).

Table 9
Score table: %, and number of checked attributes by respondents of fire risk assessment tools (model-(green), index-(orange), or not classified).

	B: Total attributes (n=103) and total number per sub-factor										
A: Sub-factors (n=10)	Management delivery (n=4)	Uncertainty (n=14)	Preventive barriers (n=2)	Fire location (n=3)	Fire development (n=4)	Repressive barriers (n=26)	Persons present (n=5)	Evacuation (n=5)	Fire and smoke (n=15)	Fire consequences (n=25)	Average in (%)
D: Classification and number of tools per class	C: % of attributes checked per sub-factor, based on a maximum number of B x D										
12 x Model Tools	4%	35%	8%	39%	67%	50%	33%	47%	50%	15%	**36,1 %**
6 x Index Tools	42%	29%	17%	44%	21%	46%	37%	53%	4%	1%	**24,9 %**
8 x Tools neither of these	0%	1%	13%	0%	0%	10%	5%	13%	10%	3%	**5,8 %**
E: Name of the tool with the number of attributes included per specific topic (n=..)	F.L.A.M.E. (n=4)	FIRE-RISK (n=12)	FIRE, Conceptual fire safety evaluation tool, MAD (n=2)	Pyrosim, Pathfinder, ISO 16732 Tool (n=3)	FIRE-RISK, FIRE, FIRECAM, Generic, Pyrosim, ISO 16732 (n=4)	Fire Strategy Evaluator (n=21)	RISKCURVES (n=3)	FIRE (n=5)	PYROSIM, MAD (n=11)	CUrisk (n=8)	HIGHEST SCORE
	Fire Strategy Evaluator (n=3)	Conceptual fire evaluation tool (n=10)		Conceptual fire evaluation tool (n=2)	AAMKS, CUrisk, B-RISK, Pathfinder (n=3)	FIRE, AAMKS, FIRECAM (n=18)	FIRE-RISK, FIRE, AAMKS, FIRECAM, CUrisk, Generik Assessment, FIERAsystem, Pathfinder, FRAME, F.L.A.M.E. , Conceptual, ISO 16732, FRIM-MAB, EvacuationNZ (n=2)	FIE-RISK, AAMKS, CUrisk, Fire Strategy Evaluator, F.L.A.M.E., EvacuationNZ (n=4)	B-RISK, Pathfinder (n=10)	FIRE (n=7)	SECOND HIGHEST SCORE

Finally, it can be concluded that aside from Yaahp as an assistant software for the decision-making process, another two tools do not contribute. (1) The Framework PBFPD Risk-Informed Performance-Based Fire Protection Design because no features were checked, and (2) the simulation tool SAFIR, because it is only a computer program that models the behavior of building structures subjected to fire.

4.5. Recommendations for future work

This study found that most fire risk assessment tools do not consider the environmental and societal impacts of building fires. The Fire Impact Tool' [46,47], is according [18], "*developed to illustrate the consequences of different tactical choices during firefighting*" and provides some implications in this perspective. It is important to collaborate with all stakeholders and to know their individual goals for developing better fire risk assessment tools. For example, it is essential for a bank to guarantee value fixed investments because of their sustainability and fire safety objectives. It is also necessary to include a form of 'building resiliency', and to know which questions must be asked to assess the desired fire safety level of a building. Therefore, we need to know the available resilience in which compliance with sustainability criteria does not adversely affect the desired fire safety level. How can we make sure that this 'space' is adequately managed by the involved stakeholder (s)? The involvement of building owners within the development process of a tool is very important because this is the stakeholder who will in the end be responsible for a fire-safe building. For the building owner it is important to know if, and to what extent, the insurance premium is in line with the actual fire risk. A fire risk assessment tool that can clarify the effectiveness of all control measures and their individual contribution to mitigate consequences will benefit the design process. This will

Table 10
Overview of fire risk assessment tools.

Name	Total number per sub-factor (N=103)											
	Management delivery (N=4)	Uncertainty (n=N=14)	Preventive barriers (N=2)	Fire location (N=3)	Fire development (N=4)	Repressive barriers (N=26)	Persons present (N=5)	Evacuation (N=5)	Fire and smoke (N=15)	Fire consequences (N=25)	Total number (N)	Total number (%)
FIRE-RISK	1	12	0	1	4	17	2	4	8	5	54	52%
FiRE	0	5	2	1	4	18	2	5	9	7	53	51%
AAMKS	1	8	0	1	3	18	2	4	9	4	50	49%
FiRECAM	0	7	0	1	4	18	2	3	9	5	49	48%
CUrisk	0	7	0	1	3	11	2	4	9	8	45	44%
B-RISK	0	9	0	1	3	13	0	0	10	0	36	35%
Generic Fire Risk Assessment	0	7	0	1	4	14	2	2	3	3	36	35%
Pyrosim	0	0	0	3	4	15	0	0	11	3	36	35%
FIERAsystem	0	3	0	1	0	17	2	2	5	4	34	33%
Pathfinder	0	1	0	3	3	10	2	3	10	1	33	32%
CRISP	0	0	0	0	0	4	1	1	3	1	10	10%
RISKCURVES	0	0	0	0	0	0	3	0	4	3	10	10%
Fire Strategy Evaluator	3	7	0	1	0	21	1	4	1	1	39	38%
FRAME	1	0	0	1	0	16	2	3	2	1	26	25%
F.L.A.M.E.	4	3	0	1	0	11	2	4	0	0	25	24%
Conceptual fire safety evaluation tool	1	10	2	2	1	5	2	1	0	0	24	23%
ISO 16732 Tool	0	4	0	3	4	4	2	3	1	0	21	20%
FRIM-MAB Fire Risk Index Method	1	0	0	0	0	15	2	1	0	0	19	18%
MAD Maximum Allowable Damage	0	1	2	0	0	5	0	0	11	1	20	19%
EvacuatioNZ	0	0	0	0	0	6	2	4	1	1	14	14%
IFC (Industry Foundation Classes) based fire safety assessment	0	0	0	0	0	2	0	1	0	1	4	4%
SAFIR	0	0	0	0	0	4	0	0	0	0	4	4%
EDGe$ Economic Design Guide	0	0	0	0	0	0	0	0	0	3	3	3%
FBIM Fire Brigade Intervention Model	0	0	0	0	0	3	0	0	0	0	3	3%
PBFPD Risk-Informed Performance-Based Fire Protection Design	0	0	0	0	0	0	0	0	0	0	0	0%
Yaahp	0	0	0	0	0	0	0	0	0	0	0	0%

also lead to more awareness and therefore a better negotiating position for the building owner with the insurer.

The authors of this paper call for establishing a steering group from both indirect and direct stakeholders. As outlined in section 4.3, two stakeholder groups can be defined: stakeholders who must bear the societal, mostly indirect burden, and those who must bear the direct financial consequences caused by a fire. The last group of stakeholders comprise: Insurers, Banks, Real estate investors, Building owners, and Private companies. Analyzing the survey answers concerning stakeholders' involvement demonstrates that the direct group of stakeholders has a substantially lower involvement in the tool developers' process. Because of this, the author of this paper wants to establish a steering group, which in the end will positively influence the tool acceptance. Newly developed tools will be more robust and therefore enhance trustworthiness.

In total eleven respondents left their remarks and/or advice in the open text boxes. Below is a summary of the most relevant responses. All responses can be requested from the corresponding author.

- Broader input from a wide range of stakeholders will be needed to help refine and gain agreement for attribute performance values amongst researchers, practitioners, and regulators in many countries by further refining and running risk assessment tools with more incident data (both success and failure).
- The occupant response time and pre-movement time are relevant and could be useful to be adopted in risk indexing methods.
- The development of these tools takes time, and it would be useful for stakeholders to put their effort together and make them available.
- It is a significant area of research whereby several respondents want to collaborate and are willing to share their source codes and are open to give feedback.
- Current risk assessment tools can learn from consequence modelling tools which are used for modelling of chemical accidents.

In this regard, two recent developments are worth mentioning.

- In section 2.1, reference was made to NFPA proposals for the development of a calculation model 'Economic Impact of Fire: Cost and Impact of Fire Protection in Buildings' 2021–2022. The first author of this paper was a member of the Project Technical Panel. The report includes five case studies [48]. The interested reader can run their own variations on the case study by using the underlying code which is available on [49]. Based on that report, a paper is published [50].
- Another development of interest is the framework SAFR-BE, for a Sustainable And Fire Resilient Built Environment [51]. It was launched in a webinar on the June 14, 2023 [52]. The following is stated in the report [53],: *"The work herein is a first step in achieving a decision support tool. In the future, additional research can lead to simpler applications and more robust decision-support tools for sustainable and fire resilient building design."*

5. Conclusions

Assessing the fire safety of a building entails the utilization of a fire risk assessment tool. The tool aims to compare the outcomes, based on preventive and proactive safety measures, in terms of fatalities, injuries, property loss, and business interruption, with the established benchmarks within their respective categories. This was mentioned by Meacham in Ref. [54] where is stated that these tools should only be used for comparative assessments. To stimulate innovation and progress in the field of fire risk assessment tools, this paper applies 12 contributing factors to assess fire risk assessment tools. When the overall score as the percentage of the covered attributes is made available to the public, competitors will challenge each other, which will lead to more tool development, and subsequently, the advancement of existing ones with enhanced predictability of the potential consequences of fire incidents.

Fire risk assessment tools can play an essential role in fire safety analysis of the built environment. Through this study, the authors have reached the following observations providing insights for further improvement of these tools:

1) It can be observed that stakeholders who experience the financial consequences/burden of a fire are not so much involved in the development of fire risk assessment tools. Hence, a greater involvement of the financial cluster is recommended.
2) Most tools focus on mitigating fire consequences instead of reducing the likelihood of a fire event occurring. More attention should be paid to incorporating other aspects of risk assessment (e.g., probability assessment, risk evaluation) to enhance the tools' capability in assisting risk-based decision-making.
3) Fire risk assessment tools based on models are better in predicting the fire consequences. But combining risk modeling with risk indexing to enhance the decision-making process could be beneficial because of simplicity, transparency, and objectivity.
4) Promising developments have been taking place but unfortunately, most of them ceased because of lack of interest and financial support.
5) To stimulate innovation and progress in the field of fire risk assessment tools, this paper provides twelve contributing factors quantifying the overall 'quality'. Eleven of the factors (section 3.3.1 to 3.3.9) cover a range of relevant features and attributes. One factor (section 3.3.10) contributes to predicting the expected fire consequences in terms of fatalities, property losses, business continuity, and/or social damage to neighbors and the environment.
6) Sustainability attributes regarding building changes over time, multi-functionalities, energy transition, and aging of the population are underserved.

   By comparing fire risk assessment tools, missing factors and attributes can be discerned to increase scientific substantiation. This lays the foundation for the field of sustainable fire-safe buildings.

   For clarity, it's important to recognize that having more attributes doesn't always equate to a better tool. This is evident when considering the benefits of specialization versus generalization. Our study doesn't suggest that more attributes invariably improve a tool; instead, it explores a spectrum of attributes relevant in various contexts. In specific scenarios, like predicting environmental impacts of fire accidents, a specialized tool with fewer, targeted attributes may be more effective. This underscores the value of both specialized and general tools in risk assessment. Comparing different risk assessment instruments presents challenges due to their variety and complexity. Despite the difficulty in directly comparing individual tools, this study has done so by quantifying the fire consequence-related attributes. Our goal is to encourage developers to share knowledge and data more openly, enhancing the development of fire risk assessment tools, especially in forecasting the consequences of fire incidents.

CRediT authorship contribution statement

Louis Cleef: Writing – original draft. **Ming Yang:** Supervision. **Britte Bouchaut:** Supervision. **Genserik Reniers:** Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Louis Cleef reports a relationship with Stichting Economie van Brandveiligheid that includes: board membership.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.firesaf.2024.104169.

Appendix

Table 1
References to fire risk assessment guidance documents (N = 12)

Guidance Documents for Fire Risk Assessment	N =
SFPE Engineering Guide: Fire Risk Assessment	9
PD 7974-7:2019 Application of fire safety engineering principles to the design of buildings. Probabilistic risk assessment (+A1:2021)	7
No	6
ISO 16732-1:2012 Fire Safety Engineering	5
NFPA 551, Guide for the Evaluation of Fire Risk Assessments	3
ISO 13387 -Application of Fire Performance Concepts to Design Objectives	3
PAS 911 Group assessment method	2
Other(s) NFPA standards for developing	1
Other(s) see the manual (Risk Cost Ass. Model)	1
Other(s): Other existing references	1
Other(s): Gretener method	1

(continued on next page)

Table 1 (*continued*)

Guidance Documents for Fire Risk Assessment	N =
Other(s): Tool is a Finite Element software that can be used to assess the expected response of the structure to fire, without reference to a specific guidance document	1
Other(s): All fire models (fire ball, jet fire, pool fire) have specific documented background. QRA method and criteria based upon Purple book	1

Table 2
Risk approaches (N = 38) * The abbreviation QRA stands for Quantitative Risk Assessment. Unfortunately, due to a spelling mistake, the survey question mentions: QRA Quality Risk Analysis. However, this has no impact on how the respondents interacted with the survey which is proven by their all ticking the quantitative tool category box.

Risk approaches	N = , out of 26 tools	Risk approaches	N = , out of 26 tools
Monte Carlo method	10	Bow-tie model	1
Event tree	9	Interview	1
QRA Quality Risk Analysis*	8	Machine learning	1
Probabilistic risk assessment	8	Big data	1
Risk index	6	Dow's Fire and Explosion Index	1
Analytical method	6	GIS Geographic Information System	1
Index method	6	Other(s): Polynomial Chaos Expansion	1
ALARP As Low As Reasonably Practicable	5	Other(s): Consequence modelling of hazardous releases based on empirical models	1
Agent Based Modelling	5	HAZard OPerability Analysis (HAZOP)	0
Risk matrix	4	SFAIRP So Far As Is Reasonably Practicable	0
AHP Analytic Hierarchy Process	3	ALARA As Low As Reasonably Achievable	0
Fuzzy theory	2	S.T.O.P. hierarchy for inherent safety measures	0
Bayesian network	2	Graph theory	0
Fault Tree	2	Petri-net	0
Failure Mode Event Analysis (FMEA)	2	SWIFT Structured What If Technique	0
Multi-criteria decision-making method	2	G1 order-relation analysis method	0
Questionnaire	2	Genetic algorithm	0
Gretener method for the assessment of fire strategies	2	Artificial neural network	0
LOPA (LAYERS OF PROTECTION ANALYSIS)	1	Information diffusion theory	0

Table 2a
(N = 7)

Risk approaches, engineering software	N = , out of 26 tools
FDS Fire Dynamic Simulator	4
CFAST Consolidated Fire and Smoke Transport	3
CFD Computational Fluid Dynamics	3
Ozone Fire Thermal Model	1
FEM Finite Element analysis Method	1
FLACS*	1
FLUENT**	0

*Gexcon FLACS (Flame Acceleration Simulator) is a Gexcon *'CFD based (pool & jet) fire modelling and highly detailed VCE modelling (Offshore, Oil & Gas industry)'* tool which is recommended by the Riskcurves respondent, also an Gexcon tool.
**FLUENT is a Computational Fluid Dynamics (CFD) code.

Table 3
Economic approaches (N = 17)

Economic approaches*	N = , out of 26 tools
Cost-benefit analysis	6
Cost-effectiveness analysis	5
Value of statistical life	5
Economic analysis	3
Net Present Value (NPV)	2
BCR Benefits Costs Ratio	2
Game theory	1
Willingness to pay	1
Utility theory	1
IRR Internal Rate of Return	1
Payback time	1
ROI (Return-On-Investment)	1
Avoided-Disaster (ROI Return-On-Investment) sometimes called Non-Disaster	1
Prospect theory	0
Human capital method	0
QALY Quality-Adjusted Life Year	0
Annuity	0

*According EDG User Guidance including NPV/ROI/IRR/BCR/Non-Disaster ROI/Value of statistical life.

Table 4
Costs of safety measures (N = 7)

Costs of safety measures	N = , out of 26 tools
(Building) Costs passive safety measures	**7**
(Building) Costs active safety measures	**7**
Maintenance costs	**6**
Replacement costs	**6**
(People) Costs organizational safety measures	**2**
(People) Costs (training, monitoring, enforcement)	**1**
Insurance premium	**1**

Table 7
Probability distributions (N = 18)

Probability Distribution	N = , out of 26 tools, (model, index, no class)
Normal	12
Lognormal	7
Discrete	7
Rectangular	5
Triangular	5
Exact	4
Poisson	3
Truncated Lognormal	3
Gaussian	2
Other(s): QRA involves multiple scenario's	1
Other(s): Pareto + uniform	1
Other(s): Weibull	1
Other(s): Largest consequences as a distribution (any)	1
Other(s): Gamma	1
Power Law	1
Binomial	1
Student-t	0
Beta	0
Other(s): Depends on the quality of the data	Deleted with reason
Other(s): Delphi method	Deleted with reason

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