Office for Product Safety & Standards

Fire Risks of Upholstered Products

Research Report

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This report was commissioned by the Office for Product Safety and Standards (OPSS)

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The views expressed in this report are those of the authors, not necessarily those of the Office for Product Safety and Standards (OPSS) or the Department for Business Energy and Industrial Strategy (BEIS) nor do they necessarily reflect government policy.

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1. Executive Summary

The report summarises key evidence which can be used to inform policy proposals relating to revision of the 1988 Furniture and Furnishings (Fire) (Safety) Regulations (FFFSRs). Information is presented on fire statistics, descriptions of fire retardant strategies, and the chemical flame retardants (CFRs) currently adopted for making furniture compliant with the FFFSRs, and the potential contribution of furniture-derived CFRs to the high background levels of these compounds found in UK indoor environments.

This is followed by a description of the methodology created to inform policy proposals by determining whether certain upholstered articles/products represent a significant fire risk based on the product type.

For the purpose of this project, we have defined "significant fire risk" which the revised FFFSRs would aim to control as: *any fire capable of causing loss of life, serious injury (debilitating effects lasting more than one month) or significant damage to property (fire damage greater than redecoration cost extending beyond the room of fire origin).*

The novel methodology has resulted in two outputs:

1. A systematic review of products identifying holistic hazards and risks associated with fire safety of furniture (risk of catching fire, fuel load and risk of fire spread, chemical exposure from flame retardants, vulnerability of users)

2. An assessment of risk factors and weighting criteria for product types to be considered for inclusion/exclusion in the policy summarising the systematic review of evidence

Analysis of fire statistics shows that most fire fatalities occur in living/dining rooms and bedrooms, they result from inhalation of toxic smoke, and most victims are elderly (48% are 65 and over, and 23% are 80 and over). Since the 1990s, fire death rates have fallen in the UK, and at a similar rate in countries such as France, Germany and New Zealand. England's fire statistics show that upholstered items (beds, mattresses and furniture) were the *material or item first ignited* in 12% of domestic fire incidents, but were responsible for 29% of fatalities, and the *main material responsible for fire development* in 16% of fires but 43% of fatalities.

The term "chemical flame retardant" ranges from naturally occurring minerals to synthetic and sometimes persistent, bioaccumulative and toxic (PBT) halogen and organophosphorus compounds. Given the wide range of potential routes to achieving compliance with the current FFFSRs, a narrow range of flame retardant chemical additives predominate as the main approaches to compliance across the UK.

The report contains a full description of, and results from, a methodology developed to rank the relative fire risk of selected furniture product types. Alongside this fire risk ranking is an assessment of the relative risk of exposure to additive chemical flame retardants (CFRs) present in each furniture product type. The results of both fire risk ranking and CFR exposure risk ranking are designed to inform policy proposals on whether to include or exclude the furniture product types from the new approach to furniture fire safety regulation currently under development by BEIS-OPSS.

The scope of the research included provision of data and an assessment tool to assist the decision to include or exclude certain *peripheral* upholstered products in the new regulations. *Peripheral,* in this context, describes smaller, specialised or less common furniture product types, to distinguish them from major product groups, such as armchairs and sofas.

The *peripheral* furniture product types included in the research scope were either small items, or possibly items that were considered as potentially posing a lower fire risk than furniture in general, because of where or how they are used. The 31 items or item clusters in scope were grouped as follows:

Product Group		Example item types in groups
• Upholstered bed components	*…including…*	headboards, footboards, divans
• Cushions and pillows	*…including…*	pillows, cushions, bean bags
• Seating and footstools	*…including…*	footstools, loose covers
• Child transportation	*…including…*	prams, pushchairs, car seats
• Baby sleep product	*…including…*	cot mattresses, cribs, baby nests
• Products for babies to nap in/sit	*…including…*	bouncing cradles, highchairs
• Products for babies to play on/in	*…including…*	play mats, changing mats
• Pet furniture	*…including…*	pet beds
• Outdoor furniture	*…including…*	outdoor furniture
• Assistive care products	*…including…*	wedges, supports, bed-rails

This list was developed from that provided by BEIS-OPSS, then expanded to include additional furniture product types with similar usage profiles. Industry stakeholders, who were interviewed as part of the research, confirmed and clarified the definitions and explanations. They also expanded our understanding of these furniture product types and how the FFFSRs and other fire safety standards and regulations apply to them.

The methodology was developed to rank the relative potential for fire injury and property damage, as well as the potential for CFR exposure, of furniture product types. It was underpinned by a systematic identification of the factors contributing to these risks, which were also mapped to understand how they were related to each other. As well as enabling an impartial and robust basis for the fire risk assessment methodology, this systematic factor identification, which was based on a comprehensive literature review, had a secondary benefit of flagging gaps in the knowledge base. Notably, there was a dearth of information describing how furniture product types are used and how that impacts fire risk, while regulatory flammability testing and related topics were very well covered.

1.1 Derivation of the key furniture safety dimensions - overview

A systematic review approach was employed to develop the concept network used to determine the appropriate dimensions for the furniture safety matrices. This can be summarised as follows:

- a targeted literature search;
- an automated keyword search of the literature;
- manual annotation, screening literature for concepts specific to furniture fire safety (and CFR exposure);
- grouping of concepts into themes;
- iterative refinement of the grouped concepts into organised networks, using input from the subject experts on the team to circumvent knowledge gaps in the literature; and
- identification of the key factors contributing to fire (and CFR exposure) risk, based on how factors are related to each other in the concept network.

This approach enabled us to cut through the extensive but not comprehensive published knowledge related to potential for fire injury, property damage and CFR exposure for furniture product types and derive the key measurable factors to be included as the dimensions of the furniture fire risk and CFR exposure potential matrices, ranking each furniture product type. The dimensions derived are presented in Table 1.

Table 1 Fire risk and CFR exposure matrix dimensions

Fire risk matrix dimensions	CFR exposure matrix dimensions
Exposure to source of ignition	Low relative body weight of user
Ignition of the item of furniture	Dermal migration
Spread of flame through the item of furniture	Oral migration

Vulnerability of nearby person to fire in item	Duration of contact
	Size of furnishing

1.2 Populating the furniture safety matrix - overview

Although measurable in principle, the majority of the risk matrix dimensions could not be populated with quantitative information because the evidence base did not support it. For example, one dimension of the fire injury/damage potential matrix was the likelihood that a furniture product type will be the first item to ignite. Understandably, unwanted fires, and particularly disastrous ones, are not carefully observed. Fire investigation involves significant assumptions, conjecture and inference in scenes of devastation. Much of this intuitive insight is lost in the granularity of fire incident reports. The resulting fire statistics are insufficient to populate this, and there was no academic literature found with modelling, testing, or other evidence that could be used instead. Removing this dimension is not appropriate given its intuitive importance to fire risk, so an alternative, qualitative approach to populating this and other dimensions was developed.

This qualitative approach asked members of the research team to complete a questionnaire, independently capturing their risk rating (on a 1 to 5 Likert scale) with underlying reasoning, for each domain, for two examples of each furniture product type. The examples of each furniture product type were selected to reflect a small, less complex and a large, more complex example of each type of item – to capture the inherent variability within a furniture product type. The team's assessments were then consolidated, following detailed discussion, and used to populate the risk matrix. Stakeholders, including the expert panel and fire investigators, were invited to complete a short version of the questionnaire (including only 5 of the 31 items in scope) in order to sense-check and validate the scoring by the team.

A statistical model was then applied to the scores so that they could be combined in a way that reflects the overall fire risk and CFR exposure risk of the furniture product types. Methods such as weighting the importance of domains based on the occurrence of specific terms in the literature were rejected in favour of a basic failure model. This was because of the aforementioned unevenness of concept coverage in the literature, and the transparency benefits of the simpler approach.

1.3 Resulting risk matrix - overview

The outputs of this methodology were lists of furniture product types ranked according to their relative fire risk and CFR exposure risk. When mapped onto a two-dimensional plot, as shown in Figure 1, the risk scores provide an effective means to differentiate between different furniture product types. Notably, most baby products are clustered together and present a relatively low fire risk but high potential for exposure to CFRs, whilst upholstered bed components present a higher fire risk and lower potential for CFR exposure. Even though variability means that the spread of risk ratings for some product types is large, this output does support a qualitative risk assessment that can aid the decision making related to the appropriateness of including different product types in the new approach to furniture fire safety.

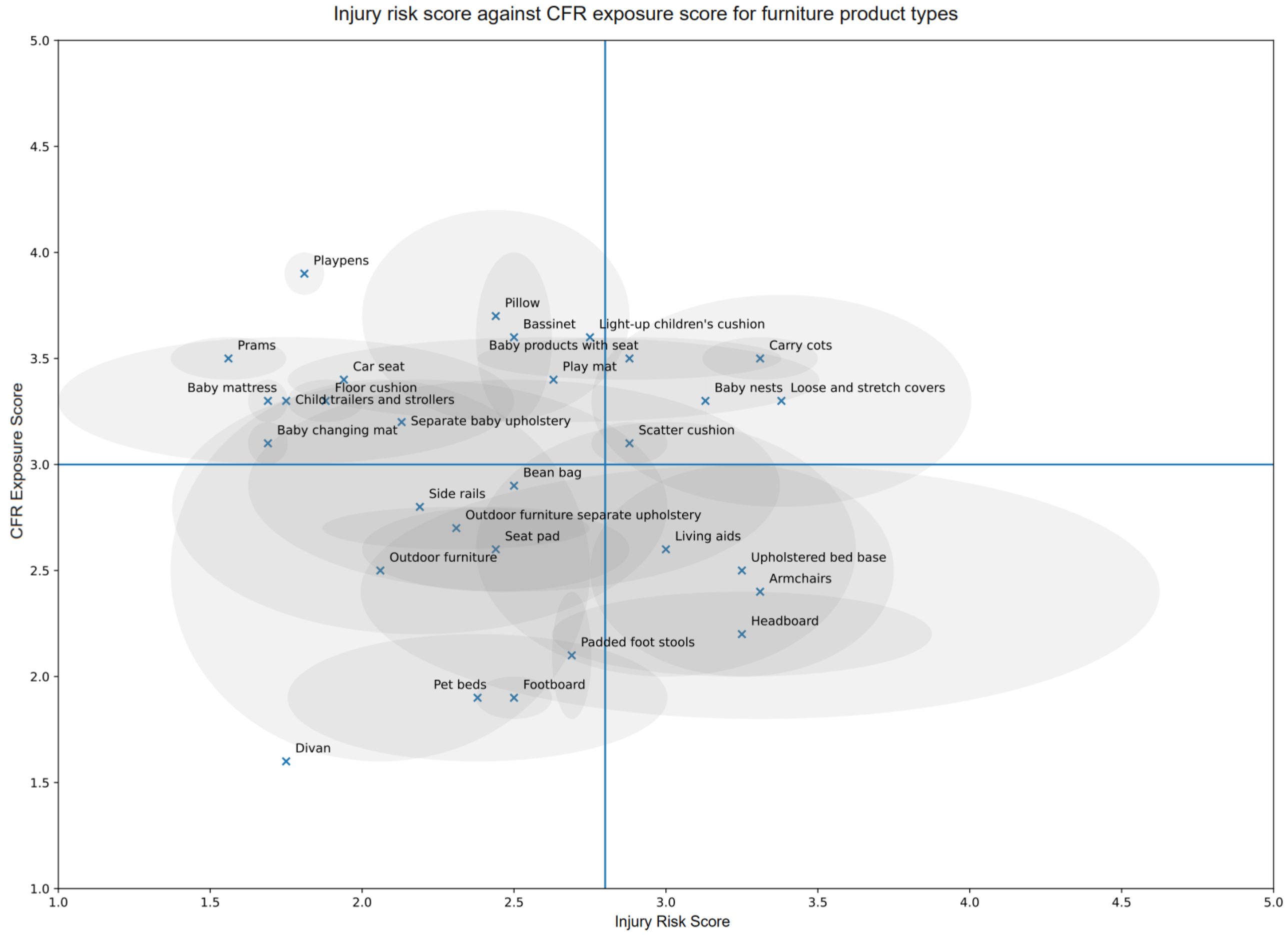


Figure 1. Plot of matrix fire risk scores versus potential CFR exposure scores, with labels for furniture types. Note that this plot does not indicate score ranges for types; these are indicated in the complete risk matrix plot in.

1.4 Limitations

The study has two parts. The first assesses the relative risks of fire and exposure to CFRs, while the second creates the *furniture fire safety risk matrix* tool to assist in deciding whether certain types of furniture products should be included or excluded from revised regulations. The lack of data regarding fire incidents is a major obstacle, as fires destroy evidence relating to the first ignited material and the material mainly responsible for fire development, particularly in serious fires.

The study employs a mixed-methods approach such that fire risk and CFR exposure models are based on literature and expert opinion. The models integrate behavioural factors and user vulnerabilities when modelling risk of injury or damage in relation to fire in furniture. The study suggests that there are specific vulnerable subpopulations that are beyond the level of resolution offered by the model, and there are potentially important secondary sources of ignition that are beyond the scope of the model.

The *furniture fire safety risk matrix* is designed to provide evidence to support policy decisions relating to the scope of the FFRs, based on anticipated CFR exposure and fire risk. The study acknowledges that the model does not suggest what approaches should be taken to ensure that furniture is fire safe, and such decisions may need to account for environmental or health implications of using potentially large quantities of CFRs to comply with fire safety tests and the behaviour of furnishings in a fire, such as smoke opacity and toxic gas production.

The material and CFR composition of individual furniture products was excluded because this was known to vary from product to product, and be a function of the existing FFFSRs. Since the aim of the project was to assess the risks of different types of furniture products, instead of individual items of furniture, neither of these concepts could be used to differentiate risk.

CFR type was not included in the furniture fire safety matrix as it did not enable differentiation between furniture product types. This effectively meant that we dealt with CFRs as a homogeneous group of compounds. Only a small subset of CFRs has been highlighted as hazardous or potentially hazardous. The problematic CFRs are mostly gas phase flame inhibitors, which are easily released from the product, and must have a volatile component to be effective. By acting in the flame, they increase the yield of products of incomplete combustion, resulting in a sharp increase in the toxicity and opacity of smoke[1]. Currently, no methodology or data exists to assess the fire safety benefits of CFR use in furniture against the potential harm caused by exposure to CFRs.

A significant amount of data is collected from individual fire incidents, in compilations of fire statistics, but they do not provide sufficient information about fire incidents involving specific product types, such as headboards or cushions. The nature of unwanted fires tends to destroy evidence relating to material or item first ignited and material mainly responsible for fire development, particularly in serious fires.

Although our analysis shows that smoke toxicity is the largest cause of death from fires, it was outside the scope of this study. A discussion on smoke toxicity has been included in an appendix, at a peer-reviewer's request. It does not feature in the furniture fire safety matrix.

A key learning from this research included the identification of gaps in the published knowledge base related to furniture fire risk and CFR exposure, which includes all the key concepts related to the matrix dimensions. The lack of usable information on the behavioural factors influencing fire ignition and flame spread in furniture product types was noticeably absent.

2. Introduction

The objective of this project is to “build the evidence base to help inform policy proposals by determining whether certain articles/products represent a significant fire risk based on the product type.”

This has been achieved using the following outputs from our research:

1. A systematic review of products identifying holistic hazards and risks associated with fire safety of furniture (risk of catching fire, fuel load and risk of fire spread, chemical exposure to CFRs, vulnerability of users).
2. An assessment of risk factors and weighting criteria for product types to be considered for inclusion/exclusion in the policy summarising the systematic review of evidence.

This work has been commissioned as part of the BEIS-OPSS’ development of a new policy approach to the existing Furniture and Furnishings (Fire) (Safety) Regulations (FFFSRs) (1988). The UK FFFSRs was introduced following a sharp increase in UK fire deaths and a tragic fire in the furniture department of the Woolworths store in Manchester in 1977. The Upholstered Furniture (Safety) Regulations were introduced in 1980, followed by the 1988 FFFSRs, which quantified the flammability of furniture, establish flammability limits, and prevent the sale of non-compliant furniture. The legislation has now been enforced for 33 years without major change. In the meantime, society and living conditions have changed: new and refurbished domestic dwellings are required to have mains-powered smoke detectors installed; fewer of society's most vulnerable members rely on open-flame heating; cigarette smoking has decreased and is often done outside. The fire fatality rate has fallen in developed western economies since the FFFSRs were introduced in the UK (See Annex 1 Detailed Fire Statistics).

The UK has amongst the highest concentrations of some CFRs in its household dust of any country in the world[2, 3]. Several CFRs have been shown to be harmful at typical UK exposure levels (See section 3.4.4). This type of information, described in more detail in section 3.4 provides an essential context from which to review the current FFFSRs and the approach to inclusion or exclusion of peripheral furniture product types.

The UK's current Furniture and Furnishings Fire Safety Regulations (FFFSRs) require all domestic upholstered furniture items to pass certain flammability tests, the test requirements varying with the item being tested. The regulations have been summarised elsewhere[4, 5]. Fabrics, fillings and composite items of furniture are all subject to testing.

The OPSS is developing a new approach to the regulations that will maintain and improve fire safety, bring the legislation into line with the approach taken for product safety for other product sectors that follow the new legislative framework (NLF), drive innovation of the ways products meet fire safety requirements to market and facilitate a reduction in the use of chemical flame retardants as the primary means for making furniture fire resistant.

It was agreed with BEIS-OPSS that the project scope was limited to items when in the home. This meant that for product types mostly used outside the home, i.e. child car seats or outdoor furniture, only their fire safety when used or stored in the home was considered.

The work undertaken, and the interactions necessary to meet the project’s objective has been summarised in Figure 2, showing the key work-packages.

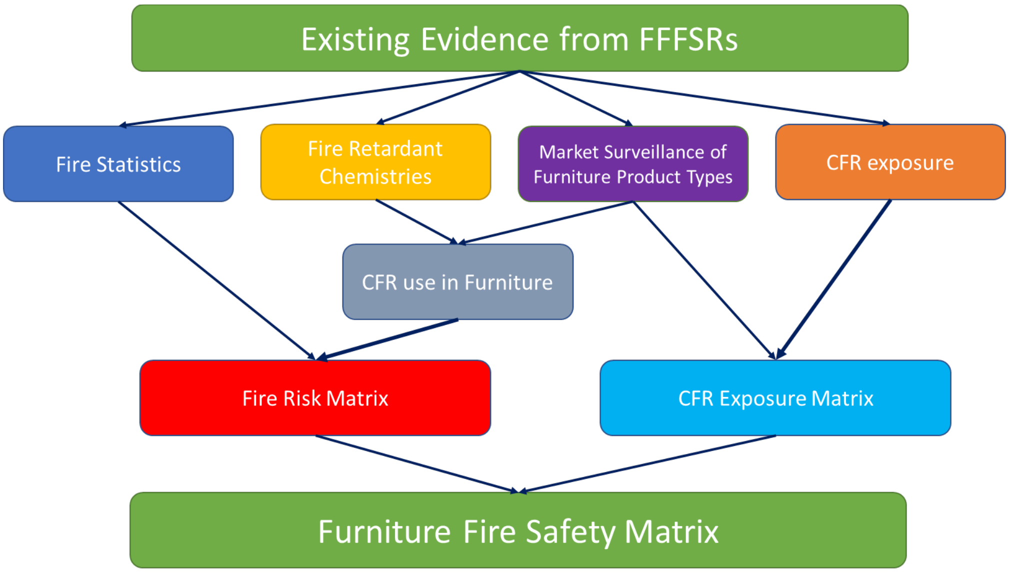


Figure 2 High-level overview of work packages undertaken to deliver the project

The report consists of six main chapters including this introduction.

- Chapters 1 and 2 are the Executive Summary and this Introduction respectively.
- Chapter 3 outlines the body of literature relating to furniture fire safety. Starting with a summary of fire statistics, for which more detail is provided in Annex 1, it moves on to describe the mechanisms by which CFRs act, with further detail provided in Annex 2, followed by more specific information on the application of CFRs to furniture. The contribution of furniture to high levels of CFRs in household dust etc., and the release mechanisms, exposure routes and health effects are then described.
- Chapter 4 summarises the methodology and results of the industry and market surveillance that was necessary to create the furniture fire safety matrix.
- Chapter 5 outlines the methodology used to create the furniture fire safety matrix, by extracting key concepts from literature and mapping these as networks in order to create two sub-models, a fire risk model and a fire retardant exposure model.
- Chapter 6 describes the resultant furniture fire safety matrix, showing the relative risk ratings for each potential hazard, and assessing the model for errors and uncertainty.
- The concluding Chapter 7 summarises the findings, and discusses their limitations, identifying areas for further research.

3. The impacts of the furniture flammability regulations on fire safety and health

This Chapter contains a comprehensive overview of the impacts of the FFFSRs on both fire safety and potential exposure to CFRs. Firstly, an overview of the statistical information on fires in domestic settings is presented and interpreted, with further detail provided in Annex 1. Next, an overview of how the materials used to make furniture are modified to comply with the regulations is presented. Also discussed is how furniture has evolved since 1988, both to accommodate new ways of achieving the fire protection required by the regulations but also in response to changing consumer preference, material pricing and manufacturing techniques. A summary of the different types of CFRs is presented, alongside an overview of those commonly used in upholstered furniture. An in-depth discussion of CFRs, which includes their classification and mode of action is provided in Annex 2 . There follows a discussion on the available knowledge on emission of CFRs from furniture, and the likely routes of human exposure and potential health effects. Finally, there is a discussion on the challenges of quantifying the benefits of CFR use in furniture, and balancing the benefits against any potential hazards.

This Chapter and Annexes 1 and 2 are important because they provide the context in which the information needed to balance the research task is being undertaken. As described in Chapter 5 (Methodology), the research team proposed a methodology that included qualitative judgements in order to answer questions related to fire risk and CFR exposure for the range of furniture product types in scope.

3.1 Fire statistics for Great Britain

Great Britain is fortunate in having some of the most detailed and consistent sets of fire statistics in the world. Fire statistics in Great Britain are based on data received primarily from the Fire and Rescue Services (FRSs). This data is gathered by each FRS independently and is then reported to government statisticians for collation and analysis. These are summarised quarterly, alongside more detailed annual reports. The FRS individual in charge of an incident at the fire scene (the Incident Commander), provides information and reports this on return to the fire station. Further details can then be added as they become available, for example the findings of a pathologist during a post-mortem of a fire victim. The analysis presented within this section is based on the government's published data for England, Scotland and Wales. Historical data was taken from the annual UK fire statistics and Fire Research Notes.

Detailed fire statistics were used in an attempt to determine the extent to which particular furniture product types (e.g. headboards, baby products etc.) contributed to fire incidents, deaths and injuries. However, the destructive nature of fire, and the difficulty leading firefighters experience in assessing the material or first item ignited and the material or product mainly responsible for fire development meant that this information was insufficiently detailed to be used as input to the fire risk model described in Chapter 5. A detailed analysis of these statistics has been provided in Annex 1, with a summary of main findings included below.

3.1.1 Fire statistics summary

- GB fire deaths have been progressively decreasing from a peak of 1100 in 1980 to around 300 in 2019.
- GB fire injuries progressively decreased from a peak around 2000, until 2015. Since then, they appear to have levelled off.
- Most fire deaths and most fire injuries result from inhalation of gas, smoke or toxic fumes.
- The likelihood of dying in a fire increases with age – many fire fatalities are very old (~25% are 80 or over), or old (~25% are 65-79).
- Most fire fatalities occur in dwellings (77%).
- Most domestic fires start in kitchens (54%), with 12% starting in living/dining rooms, and 10% in bedroom/bedsits.

- Most domestic fire fatalities occur in living and dining rooms (42%), and bedrooms/bedsits (30%), with only 16% in kitchens.
- The fatality rate of living/dining room (23%) and bedroom/bedsit (20%) fires is 10 times greater than that of kitchen (2%) and 6 times greater than other dwelling fires (3.3%).

3.2 Fire retardants

3.2.1 Introduction

Fire retardants are substances added to combustible polymer products to reduce their flammability. In general, most fire retardants are more expensive than the polymers they are protecting, so they are only added to meet regulatory requirements. There are a diverse range of potential fire retardants with over 200 being commercially available. They can be subdivided by their chemistry (e.g. halogenated, phosphorus, metal hydroxide etc.), their mode of action (gas-phase flame quenchers, char formers, heat absorbers etc.), or their attachment to the host polymer (additive or reactive).

ISO define a *fire retardant* as substance added, or a treatment applied, to a material in order to delay ignition or to reduce the rate of combustion[6]. They define a *flame retardant* as a substance added, or a treatment applied, to a material in order to suppress or delay the appearance of a flame and/or reduce the flame spread rate[6].Thus *fire retardants* can act anywhere to reduce flammability, by releasing water, absorbing heat, forming a protective char or barrier layer, but also include the sub-set *flame retardants* which act by interfering with reactions in the flame. In the context of furniture flammability, this distinction is important: by interfering with the flame chemistry, flame retardants produce more smoke and products of incomplete combustion, where many other types of fire retardant keep the fuel out of the flame zone. Fire retardants which act in the gas phase, interfering with flame reactions, *flame retardants,* are frequently applied to upholstered furniture products. For the purpose of this report, it is not always necessary to draw such a distinction, in which case the generic abbreviation CFR, for chemical fire/flame retardants will be adopted.

Fire retardants have evolved over the last four decades in order to meet the demands of industry and regulators, from halogen-based flame inhibitors to char promoters, which result in less smoke and toxic gas emissions. While halogenated flame retardants continue to be used in a wide range of existing products, very little new work has been published describing technological development and improved performance. Instead, published research has been heavily focussed on finding suitable halogen-free replacement fire retardants, indicating that the need for change has been acknowledged, in the face of increasing pressure, predominantly resulting from environmental concerns.

In the 1970s halogenated flame retardant chemicals started to be used to make products less flammable[7]. Halogenated flame retardants act by releasing hydrogen bromide (HBr) or hydrogen chloride (HCl) which interferes with the gas phase free radical reactions of a flame, Preventing the main heat release reaction converting carbon monoxide to carbon dioxide, and in so doing they produce more carbon monoxide, smoke and other products of incomplete combustion[8]. Addition of antimony trioxide, which has no flame retardant effect on its own, significantly enhances the fire-retardant performance of halogenated flame retardants (by increasing their residence time in the flame zone). The antimony-halogen combination has been widely used in UK furniture[9]. Halogenated flame retardants are effective in most polymer systems, where some other fire retardants are only effective, or compatible with in one, or a few polymer systems. This ease of formulation has encouraged the widespread use of halogenated flame retardants.

In contrast, many other types of fire retardants reduce fuel release to the gas phase, often by formation of a protective char or barrier layer, which acts as a radiation shield, and inhibits the flow of fuel out, and heat and oxygen in. Such barriers have also been deployed in intumescent systems, where gas is released within the molten polymer, causing significant swelling, and so increasing the effectiveness of the thermal and physical barrier. However, the formulations required for char promotion and intumescence are often specific to a particular polymer, requiring a larger number of trial formulations to be made-up and tested before a suitable candidate is available for optimisation. They are less suited to fabrics and foams than to solid polymers.

Phosphorus-based fire retardants fall into both categories (flame quenchers and char promoters). Phosphates (consisting of a central phosphorus atom attached to four oxygen atoms) are non-volatile and only act in the condensed phase as char promoters. Substituting oxygen with carbon, forming phosphonates and phosphinates increases the volatility, and the shift towards gas phase fire retardant action.

3.3 Fire Protection of Furniture

The sharp rise in UK fire deaths and injuries around 1980 coincided with rapid uptake of low-cost polyurethane foam filled furniture and resulted in the 1980 and 1988 Furniture and Furnishings (Fire Safety) Regulations (FFFSRs), the latter banning the sale, new or second hand of upholstered furniture for domestic use not meeting stringent flammability criteria.

3.3.1 Summary of current FFFSRs and how they are complied with

The structure of the regulations allow a wide choice of fabrics and furniture designs to be compliant with the UK's FFFSRs, as both the fabric and the filling ("components") must meet the flammability requirements separately. The finished "composite" (fabric and filling) combined into a seat shaped configuration also needs to be tested.

Fabrics can achieve compliance with the FFFSRs in several ways:

1. Use of an inherently low flammability fabric. For example, wool and leather fabrics are available which do not require addition of CFRs to be compliant with the FFFSRs.
2. For synthetic polymers, fire retardant moeties can be incorporated into their chemical structure (covalently bonded to the polymer chain) before being spun into yarns. These are known as *reactive* fire/flame retardants, and mitigate release of any CFRs during the product's lifetime.
3. For synthetic textiles, CFRs can be incorporated into the polymer melt before spinning into a yarn[10]. This is likely to reduce their release into the environment.
4. For natural fibres, which tend to be more absorbent than their synthetic counterparts, chemical treatments can penetrate the fibre, and in some cases covalently bond onto it. Examples include Proban® treated cotton and Zirpro® treated wool.
5. Applying an additive fire retardant bound in a flexible matrix to the inside surface of the fabric, known as back-coating, is a well-established and commonly used method for meeting the FFFSRs[11]. The back-coating is frequently latex-based and contains a high fire retardant loading[12]. There is a significant chance that CFRs will be released during the product's lifetime, as the fabric moves, and the latex degrades. This may increase the ignitability of the product, as well as contributing to exposure to CFRs.
6. Adding CFRs in aqueous solution to the fabric (pad-coating, or pad-cure-dry coating), allowing impregnation followed by drying and curing is an older technique which may also suffer the disadvantages associated with release of CFRs[12].

The fabric is tested for "match ignition resistance" using a standard method (a small gas flame) described in BS 5852[13], when the fabric is covering a piece of standard, non-combustion modified (i.e. non-flame retarded) polyurethane foam[5].

An alternative approach is through the use of interliners, or barrier fabrics, which are covered in the BS5852 test requirements for use with certain "natural" fabrics.

The filling must also pass a regulatory test. For polyurethane foam the test involves covering the foam with a standard cotton fabric and testing a seat configuration with a crib #5 ignition source. To meet this requirement flexible polyurethane foam normally contains around 5% of an additive fire retardant, usually from the tri-chloroalkyl phosphate family[14], most commonly tris(1-chloro-2-propyl) phosphate (TCIPP). As some tri-chloroalkyl phosphate-containing products are under scrutiny from ECHA, foam manufacturers are producing alternatives[15].

Usually, the fabric manufacturer/processor combines the foam and fabric into the finished article, or a rough replica of it, such as a padded seat, using a "worst-case" filling for a final composite test, which must be cigarette ignition resistant[5]. Although the composite cigarette test is usually passed by all compliant components, the complex interactions between fabric and foam during burning mean that it is not possible to predict the actual fire performance of the final furniture product, despite compliance in the separate fabric and foam component tests[16, 17]. Between 1993-95 a large joint European project[18, 19] (CBUF) studied the fire behaviour of upholstered furniture fabrics and fillings in 225 large scale tests and 1270 cone calorimeter tests, providing a significant understanding of how furniture burns, how furniture composition affects the heat release rate, and how well or poorly different models predict full-scale test results and the developing hazard to people. It established robust methodologies for assessing fire performance and predicting fire behaviour from cone calorimetry bench-scale to large-scale but concluded that it was not feasible to predict the performance of composites from individual component tests.

The UK's furniture industry is divided into a number of component manufacturers, through a supply chain, which ultimately leads to the final furniture product manufacturer. Typically, one manufacturer will purchase yarn and weave it into a fabric, another will apply the fire retardant treatment and test it to demonstrate it meets a particular standard, and finally the furniture product manufacturer (or upholsterer) will incorporate the fabric into their design. Similarly, the fillings, such as flexible polyurethane foam, are formulated at the foam producer, where the CFRs are added to the polyol, before reaction with the isocyanate to produce the foam, again, tested by the foamer to meet the regulatory flammability requirement. The foam is cut into shape, often by a separate "foam converter", before being incorporated into the furniture product by the upholsterer. This is relevant because in most cases the upholsterer only knows that the fabric and foam have met the relevant flammability performance requirements but has no knowledge of the fire retardant treatments or loadings used to achieve them.

In the UK, small manufacturers tend to rely on their suppliers for testing and certification, whilst larger manufacturers carry out due diligence testing on incoming batches of textiles, and of fillings, following the test methods defined in the regulations[20].

A recent report[4], commissioned by BEIS-OPSS and written by the Building Research Establishment (BRE) describes consultations with the furniture industry in relation to the FFFSRs, who felt they needed to be updated to reflect the change in environment seen in the modern home. It emphasised they need to consider alternative smouldering sources given that the only cigarettes available in the UK are reduced ignition propensity (RIP) which are considered insufficient to cause ignition of furniture items. Following the introduction of self-extinguishing, or RIP, cigarettes across Europe in November 2011, this concern was expressed[21] for carrying out testing to EN 1021-1[22]. However, when tested on upholstery it was found that RIP cigarettes burnt their full length, and so could be used for the testing of upholstered furniture composites. However, there may be an increased incidence of cigarettes not smouldering their full length. Therefore, it was agreed that moving to three ignition sources (cigarettes) rather than the current two would address this effectively.

The furniture industry also suggested that the use of testing fabrics over non-combustion modified foam should be reviewed and standardised, given that the current foam was not widely available in the UK, there were no commercial applications for it, and it is unrepresentative of anything that could be used in UK furniture.

3.3.2 Use of CFRs in furniture

As described above, one way in which the requirements of the FFFSRs may be met is by treating the foam filling and fabric covering of furniture with chemical flame retardants (CFRs). In this section, we provide a brief overview of the different types of CFRs available and the extent to which they are used in furniture.

It is important to note that use of CFRs is widespread and not in any way restricted to furniture fillings and fabrics. Thus, use of CFRs in domestic furniture is not the only source of human exposure to such chemicals. As just two examples, CFRs are also applied to the printed circuit boards and the hard plastic casings of many electrical and electronic goods, as well as rigid polyurethane and polystyrene building insulation foam. They are also widely employed in office furniture, as well as in foams and fabrics in private and public vehicular environments. Moreover, there are a wide range of CFRs in use (see section 3.2), as well as inherently flame retardant materials available that may meet the requirements of various fire safety regulations. Thus, within a given class of furniture product type, such as a sofa, different CFRs will be applied. Figure 23 summarises global consumption of different categories of CFR used across all applications. It should be noted that the category of organophosphorus FRs, includes two chlorinated organophosphate esters (TCIPP and tris(1,3-dichloroisopropyl) phosphate (TDCIPP)), that are widely applied to flexible polyurethane foam used in furniture[23, 24].

As described earlier, in furniture, CFRs are – if employed – are often used in the filling and the internal, filling-facing surface of the fabric covering – the latter process is referred to as "back-coating". There are two fundamental ways in which CFRs are applied, namely: (a) **reactive**, whereby the CFR is chemically bound to and becomes an integral component of the foam or fabric, and (b) **additive**, whereby the CFR is dissolved into or distributed (e.g. sprayed) on to the foam or fabric.

As noted, a range of CFRs may be applied in furniture. In flexible polyurethane foam (PUR) used in the UK and Ireland, TCIPP and TDCIPP are amongst the most common currently used CFRs. In this context, the EU risk assessment report (RAR) for TDCIPP notes that most TDCIPP is used in the production of flexible polyurethane (PUR) foam[23]. However, the same document further notes that use in furniture foam (as opposed to car seat foam) accounts for ~15-20 % of total EU use of TDCIPP. Moreover, the EU RAR for TCIPP records that the majority (80%) of TCIPP applied in the EU was used in rigid PUR foam for construction applications, with flexible PUR foam in upholstery and bedding accounting for a further 17%[24]. It should be noted that this latter figure will likely be greater in the UK, as the EU RAR notes that TCIPP use in flexible foam for furniture was for the UK and Irish market[24]. Further evidence of the widespread application of these chlorinated organophosphate esters (OPEs) in furniture foam on the UK market is provided by analysis of waste furniture foam samples. Specifically, 3 out of 4 waste domestic and office furniture foam samples collected in 2011-12, contained TCIPP at concentrations ranging from 0.84 % to 1.7 %. In the same study, 4 out of 5 office furniture foam samples contained TCIPP at between 1.6 and 3.8%, with the other office foam sample containing TDCIPP and tris(2-chloroethyl)phosphate (TCEP) at 1.1 and 0.5% respectively[25]. There are reports that TCIPP has been the preferred FR used in the production of UK PUR foam for domestic and office applications due to lower production costs than similar FRs such as TDCIPP [23].

With respect to back-coating of furniture fabrics, evidence suggests that until the introduction of bans on their new use, both decabromodiphenyl ether (Deca-BDE) and hexabromocyclododecane (HBCDD) were used in the UK. European manufacturing companies represented by the European Brominated Flame Retardant Information Panel (EBFRIP) estimated that approximately 9% of HBCDD sold by them into the UK was used for textile manufacture[26]. By comparison, application of Deca-BDE to furniture fabrics was more significant with such use in Europe occurring predominantly in the UK[27] . While exact use volumes are not available, in 2012, the proportion of DecaBDE used in the EU in textiles and other uses (as opposed to plastics) was placed at 48%[27]. Consistent with this, the Environment Agency's environmental risk evaluation of Deca-BDE noted that the main ongoing European use of this CFR appeared to be for textile applications[28] . With respect to empirical evidence of the use of such CFRs in furniture fabrics, HBCDD was detected in one out of 15 domestic waste furniture fabric samples[25] collected in the UK in 2011-12. More recently, out of 22 samples of furniture fabrics collected from waste sites in the Republic of Ireland in 2015-16, HBCDD was present at concentrations between 2.1 % and 5.1 % in 6 samples; while decabromodiphenyl ether was detected at between 0.3 % and 7.3 % in 6 samples[29]. However, the bans on new use of both Deca-BDE and HBCDD, have likely led to the use of alternative CFRs to back-coat furniture fabrics. One likely such CFR is decabromodiphenyl ethane (DBDPE). The Environmental Risk Assessment of DBDPE conducted by the EA in 2007 noted its applications to be similar to those of Deca-BDE. While it was noted that production figures were not available, nor information on the relative quantities used in furniture fabrics compared to electrical and electronic equipment (EEE); information from DBDPE manufacturers that furniture fabric use was relatively low compared to polymer applications was cited[30]. However, recent (March 2019) evidence to Parliament from a professional working in the UK fabric industry noted that DBDPE is currently used to back-coat furniture fabrics[31] .

Most recently, a survey[9] commissioned by the Environment Agency took 282 items of different components of UK waste domestic seating (fabric, filling etc). All samples were screened for the presence of bromine. Bromine exceeded 1% by weight in 54% of textile covers. Subsequent measurement of PBDEs and HBCDD in 50 of the same samples (all but one of which contained bromine >0.3%), revealed decabromodiphenyl ether or HBCDD to be present at >1% in 17 out of 21 textile covers analysed. Chlorinated organophosphate ester flame retardants were also found in 16 of 20 samples subjected to further analysis, 12 containing >0.1%, and 4 containing >1%.

In addition, a range of non-halogenated and oligomeric CFRs have been reported to be used in furniture in both foam and fabric coverings. Examples reported to be present in furniture available on the French market (where generally only resistance to cigarette ignition is required) include: triphenyl phosphate (TPhP), resorcinol diphosphate (RDP), melamine, Bisphenol A Bis-(diphenyl phosphate) (BAPP), and Tris(4-isopropylphenyl) phosphate (iTPP)[32] . Moreover, other additive CFRs reported to be applied in furniture foam include: aluminium diethylphosphinate (ADP), as well as phosphorus based additives like phosphonates, phosphoramidates, and methyl-9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide (methyl-DOPO)[33]). Overall however, reliable data on the relative penetration of the various CFRs of the UK domestic furniture market does not appear to be available.

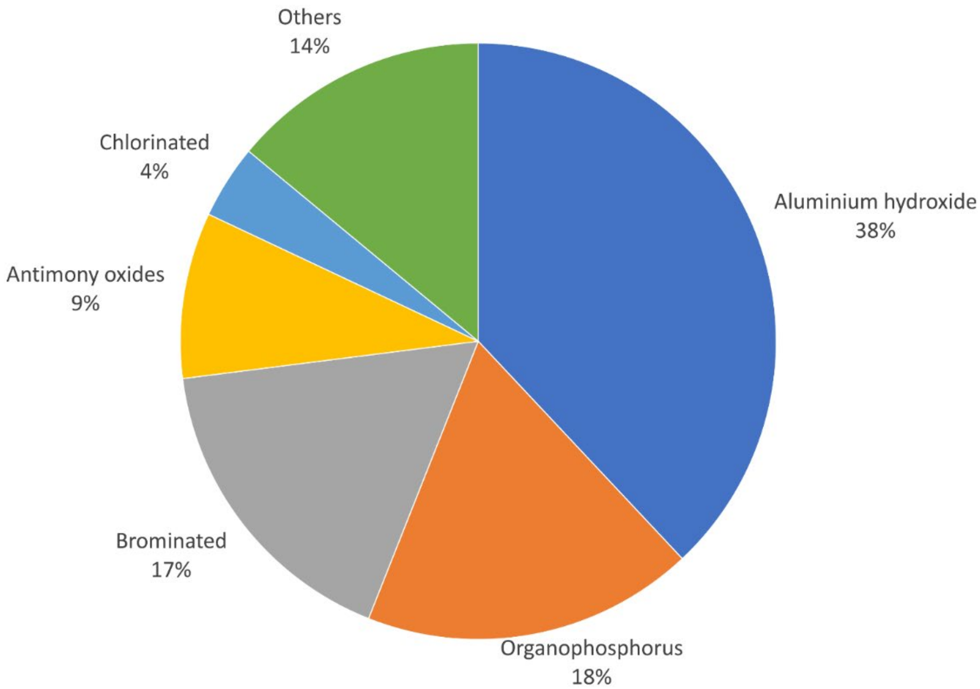


Figure 3 Global consumption of CFRs according to CFR category in 2019 (taken from ***https://www.flameretardants-online.com/flame-retardants/market*** *accessed 6/8/2021)*

3.4 Release of chemical flame retardants used to comply with furniture flammability regulations

The processes via which CFRs used in furniture may be emitted into the environment, the extent to which this occurs as well as the consequences for human exposure have been summarised below. Although outside the remit of this project, we also provide an overview of current health concerns that arise from such exposure, as this is important contextual information that helps understand concerns about human exposure to CFRs used in furniture.

3.4.1 Mechanisms via which chemical flame retardants are emitted from furniture

Research has identified the mechanisms via which CFRs may be emitted into the surrounding environment from the furniture foams and fabrics within which they were incorporated. This comprises both controlled laboratory experiments examining transfer of TPhP, TBPP, TCIPP, TDCIPP, and HBCDD from treated furniture foam and fabrics to air and dust, as well as forensic microscopic identification of CFR-containing fibres in dust collected from homes and other indoor microenvironments, Figure 4 summarises these mechanisms.

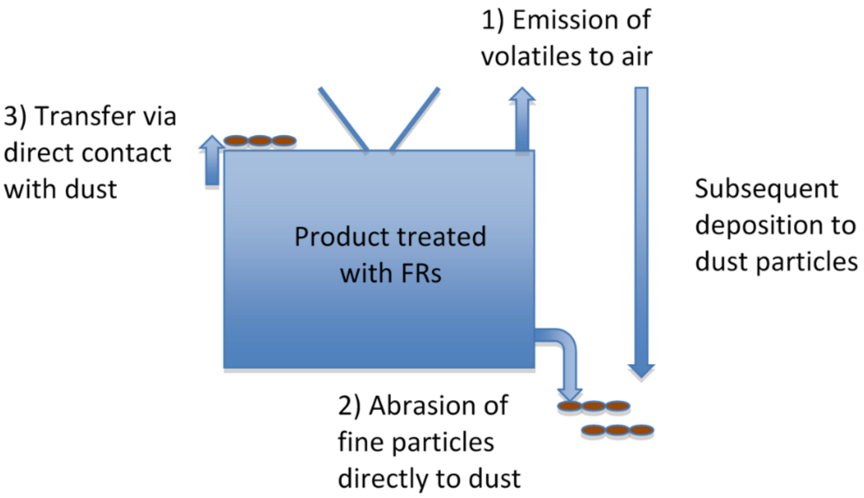


Figure 4 Mechanisms via which chemical flame retardants may transfer from treated products into air and surface/suspended dust.

In summary, they comprise:

1. Volatilisation[102, 34, 35, 36, 37, 38, 39]
2. Abrasion of fibres/particles of furniture fabric covers and/or particles of exposed furniture foam[102,38].
3. Diffusion of CFRs from the surface of treated fabric covers or exposed foam into a medium in direct contact with such surfaces[102, 34 ,35, 40]. These may include dust particles settled on the surface of source items, clothing, or exposed skin of furniture users.

Because they are chemically bound to the furniture polymer matrix, emissions of reactively incorporated CFRs (see section 3.4.1) via mechanisms 1. and 3. above are much lower than for CFRs incorporated in an additive fashion[17]. It is important to note though, that reactive CFRs may still be emitted from furniture via abrasion of fabric fibres or exposed furniture foam particles.

3.4.2 Pathways via which human exposure to chemical flame retardants may occur

Emission mechanism 1 above can lead to human exposure via: inhalation of volatilised vapours, via atmospheric deposition to suspended dust which is subsequently inhaled, or via atmospheric deposition to dust settled on room surfaces, which may subsequently be either deliberately (as a result of geophagic behaviour, most common in young children) or inadvertently ingested. Inadvertent ingestion of settled surface dust and associated contaminants is considered greater amongst toddlers than adults or older children due to the former's closer proximity to floors and more frequent and prolonged hand-to-mouth behaviour[41, 42]. There is also potential for dermal uptake of contaminants present in dust or the vapour phase.

Exposure stemming from mechanism 2 follows incorporation of such abraded fibres and particles into both suspended and settled dust[36]. Exposure can then occur via inhalation of suspended dust or ingestion of settled dust as described for mechanism 1.

Finally, mechanism 3 contaminates settled dust, with possible exposure ensuing via ingestion of such dust. More importantly, it may result in dermal exposure, either via skin contact with clothing or other fabrics (e.g. sheets/pillowcases) in contact with both the flame retarded item and skin; or direct skin contact with the flame retarded item[102,43,,44].

Direct exposure to CFRs in furniture items may also occur via "mouthing" of the item. Mouthing of objects is an activity practised mainly by young children. It is considered a potentially important pathway of exposure to CFRs and related chemical additives present in plastic toys either by dissolution of the chemical into saliva[45, 46], or by direct ingestion of particles or fibres of the item mouthed[47] – indeed the Toy Safety Directive assumes ingestion of 8 mg of plastic toy per day[48]. While we are unaware of studies that have examined mouthing as a pathway of exposure to CFRs in furniture, mouthing by young children of furniture and consequent exposure appears highly plausible.

In addition to the above exposures that occur indoors (i.e. in the "near-field"), many halogenated flame retardant chemicals are sufficiently persistent and hydrophobic that following emission (e.g. via ventilation and wastewater) they are capable of undergoing ubiquitous environmental transport and bioaccumulation in both terrestrial and aquatic organisms. As a result, "far-field" exposure accrues via the diet, including to current use CFRs such as DBDPE[54] and organophosphate esters[49]. Moreover, UK nursing infants receive exposure (18 ng/kg body weight/day) to current use halogenated FRs via ingestion of human milk, that is sixteen times the dietary exposure of UK adults[54]. That human body burdens of CFRs arise from multiple sources and exposure pathways, is consistent with the observation of a weak correlation ($R^2 = 0.06$) of metabolites of organophosphate FRs in human urine (n = 229) with emissions from furniture[50] .

3.4.3 Magnitude of human exposure to chemical flame retardants

Near-field indoor exposures to a range of now-regulated brominated flame retardants have been shown to contribute substantially to human body burdens and to be particularly elevated for young children[51]. Moreover, such exposure considerations coupled with concerns over adverse effects on humans and wildlife have contributed materially to the listing of Deca-BDE and HBCDD (both previously used to flame retard furniture fabrics) under the UNEP Stockholm Convention on persistent organic pollutants. Exposure to CFRs currently used in UK furniture such as OPEs and DBDPE has been characterised in numerous jurisdictions, including the UK and the Republic of Ireland (whose furniture flame retardancy regulations are similar). Emissions of and exposures to both OPEs and DBDPE are the result of similar mechanisms and pathways to those described above. Moreover, concentrations of DBDPE in settled dust from Irish homes, offices, cars, and school classrooms are the highest reported to date globally[52], leading to "typical" and "high-end" exposures via dust ingestion that are 1.3 and 120 ng/kg body weight/day for a 70 kg adult, and 21 to 2500 ng/kg body weight/day for a 10 kg toddler. Meanwhile concentrations of DBDPE in UK house dust have increased significantly over the last decade[53]. Analysis of UK foodstuffs also reveals the presence of a range of current-use halogenated flame retardants at concentrations comparable to those of banned brominated flame retardants[54]. This is reflected in increased detection frequency (from 0% in 2010 to 19% in 2014-15) of DBDPE in human milk in Ireland[52], as well as increases in the detection frequency of DBDPE and several other current-use brominated flame retardants in breast milk from UK mothers[54]. Specifically, while the detection frequency of DBDPE in UK human milk increased only marginally (from 4% to 10%), those of α- and β-tetrabromoethylcyclohexane (DBE-DBCH), 1,2-bis(2,4,6-tribromophenoxy)ethane (BTBPE), and 2-ethylhexyl-2,3,4,5-tetrabromobenzoate (EH-TBB) rose from 20% to 100%, 76% to 100%, 28% to 40%, and 36% to 50% respectively[95]. With respect to OPEs, concentrations in UK indoor dust from homes, school classrooms, offices, and cars, exceeded those of most legacy BFRs, with concentrations of TDCIPP (at 740 µg g^{-1}) and TCIPP (370 µg g^{-1}) detected in two UK car dust samples amongst the highest reported in indoor dust from any microenvironment anywhere in the world[55]. Moreover, concentrations of TCIPP in UK house dust exceed significantly those in house dust from Australia, Canada, and Germany[56]. That exposure to CFRs is not limited to halogenated monomeric chemicals is demonstrated by the presence in UK indoor dust of oligomeric and non-halogenated monomeric CFRs at concentrations exceeding those in Norway[57] . Particularly pertinent is the detection of the CFR V6 (2,2-bis(chloromethyl)propane-1,3-diyltetrakis(2-chloroethyl) bisphosphate), as this CFR has been reported to be applied widely to flexible PUF used in domestic furniture and childcare products[58].

3.4.4 Health effects

As mentioned above, evidence related to adverse human health impacts (e.g. impaired neurological development) contributed materially to the listing as persistent organic pollutants of brominated flame retardants previously used in furniture fabrics. Moreover, the continued presence of such chemical contaminants (i.e. polybrominated diphenyl ethers (PBDEs) and HBCDD) in materials remaining in use in UK homes, has been reviewed by the UK's Committee on Toxicity (COT). Specifically, recent COT statements note "potential concern (about) PBDE-99 and -153 exposure (of young children) from breast milk at age 12-18 months, and for exposure to PBDE-99 and -209 in dust and soil in children aged 1-5 years"[59]. With respect to HBCDD, the COT stated that "while the level of HBCDDs in the diet of infants and young children is not a cause for concern, the possibility of high levels in household dust continues to be so", citing a toxicological reference point of 3 µg/kg bw/day based on a toxicological endpoint of adverse neurobehavioural outcomes[60]. Evidence exists of the toxicity of PBDEs in animal studies to the liver, thyroid hormone homeostasis, and the reproductive and nervous systems60. Moreover, previous work has that while adult exposure to BDE-209 does not exceed the USEPA's reference dose (RfD) of 7 µg/kg bw/day (driven by an endpoint of neurodevelopmental toxicity), exposure of some UK children to BDE-209 via ingestion of indoor dust alone (i.e. not taking into consideration other exposure pathways), does exceed this RfD value[61]. With respect to flame retardants not currently subject to restrictions, the USEPA's 2014 assessment of alternatives to BDE-209, rates DBDPE a similarly high hazard to BDE-209 with respect to developmental toxicity[62].

ECHA's 2018 draft recommendation that the use of such Cl-OPEs in children's foam products and residential upholstered furniture should be restricted summarises evidence of the carcinogenicity and reproductive toxicity of chlorinated OPEs (Cl-OPEs) like TCEP, TCIPP, and TDCIPP[104]. Such evidence, coupled with that of exposure (predominantly dermal[63]) to such Cl-OPEs in polyurethane foams, are described in ECHA's 2018 draft recommendation that the use of such Cl-OPEs in children's foam products and residential upholstered furniture should be restricted. As noted above in section 3.3.2, this recommendation has yet to be acted upon awaiting the overdue outcome of studies by the US National Toxicology Program on the carcinogenicity of TCIPP. Moreover, TBPP commercial mixtures which include TPhP have been found to be reproductive toxins and have carcinogenic, neurotoxic, and endocrine-disrupting properties[102]. However, it is important to note that the UK COT recently stated that current use phosphate-based CFRs did not pose a risk of developmental toxicity at anticipated exposure levels. The COT noted that phosphate-based FRs were very unlikely to share the neurodevelopmental effects of other organophosphate chemicals but could not exclude the possibility that phosphate-based FRs could produce neurodevelopmental toxicity by some other mechanism[64].

Compared to older children and adults, when normalised to their body weight, young children such as toddlers are more highly exposed to chemicals such as CFRs[65]. The higher exposure of young children stems from a combination of greater hand-to-mouth and mouthing behaviours[66, 67] as well as a high surface area to volume ratio, and a lower body weight that means children's exposure to a unit quantity of chemical is greater when normalised to their body volume or weight[68]. With respect to the health effects arising from such higher exposure levels compared to adults; children's metabolic pathways are immature, and their ability to metabolise toxic chemicals differs from adults. While in some cases, this may lead to lower risk than adults because children cannot convert chemicals to their toxic forms; children are generally considered more vulnerable because they lack the enzymes needed to break down and remove toxic chemicals[69].

3.5 CFR use in furniture - risks versus benefits

Put simply, every fire death is a tragedy. Moreover, many fire injuries lead to permanent impairment, whether through burns (skin damage or loss of limbs), breathing difficulty or psychological problems (some of which have physiological causative factors linked to carbon monoxide uptake). Furthermore, fire deaths and injuries are precisely quantified and widely reported.

In contrast, the adverse health effects of exposure to CFRs are more subtle, and causation is much more difficult to prove. However, the voluminous evidence in the scientific literature of ubiquitous exposure via multiple pathways to CFRs, evidence of the resultant health impacts, and the very much larger numbers of people exposed to CFRs (effectively the entire population) than housefires; suggests that the benefits of achieving furniture fire safety via widespread use of some CFRs may not come without at least some undesirable human health impacts. Indeed, such considerations have undoubtedly contributed to bans on the manufacture of several halogenated CFRs.

There have been several studies that have evaluated the risks and benefits of the use of CFRs in furniture. In one, the authors concluded there to be “no fire safety benefits” of the Californian furniture flammability standard (TB117), while there was “documented” “environmental harm”[70]. A similar conclusion was reached by the authors of another study[71] , who stated that “that the use of FRs in domestic upholstery does not seem to be justified due to potential risks and a lack of clear benefits.” A third paper reported data from empirical studies of both CFR exposures resulting from simulated furniture use and flammability performance of furniture constructed using four different CFR technologies[102]. Specifically, these were: no CFR added to the polyurethane foam (as a control), a commercial TBPP mix added to the polyurethane foam, a reactive (polymer integrated) CFR incorporated in the polyurethane foam, and no CFR added to the polyurethane foam, but a barrier material added between the polyurethane foam and textile cover. In addition, a chair cushion in which the polyurethane foam was treated with TDCIPP was also evaluated for CFR exposure. Exposure via inhalation, dust ingestion, and dermal uptake was only demonstrated where additive CFRs (TBPP and TDCIPP) were used in the polyurethane foam, with exposure not detected for products using the other technologies. Moreover, the study’s open flame fire data indicated that while the use of a barrier had a remarkable impact on the burn parameters of the upholstered chairs, the use of CFRs, as defined in the study, did not. The authors concluded that “the chair fabricated with a barrier without CFRs showed a remarkable reduction of open flame hazards, offering a significant advancement to reduce fire and chemical exposure risks.”[102]. In contrast, a fourth study concluded that “flame retardants introduced in upholstered furniture present no risk if: (a) flame retardants and products using them comply with the REACH regulation…and (b) the furniture complies with cigarette ignition and match ignition requirements”[72]. The starkly contrasting conclusions of these studies exemplifies the difficulty in evaluating the relative risks and benefits of CFR use in furniture.

4. Landscape review of product types, built on input from industry

4.1 Integrating input from industry experts

A series of industry expert interviews were carried out to expand the project team's understanding of the products on the list, with a focus on the furniture, baby products, and assistive care products (Table 2).

Table 2 Industry interview details

Name	Job Title, Company	Target information	Date of interview
Julie Milne and Robert Anslow	Membership & Technical Support Manager and Managing Director Baby Products Association	Baby product categories, typical materials, suppliers and FRs	08/07/2021
Expert name withheld	Expert affiliation withheld, both at expert's request	Baby product categories, typical materials, suppliers and FRs – with particular attention on baby transportation products	13/07/2021
Angela Moran	Head of Product Development, Silentnight	Insight on materials used for upholstered bed products and cushions/pillows.	06/07/2021
Gareth Mayhew	Head of Risk and Compliance at TCM Living Group	Cushion, seating and footstool product definitions sense-check and insight on materials, suppliers and FRs.	07/07/2021
Barend ter Haar	Director, BES Healthcare, as well as secretary of TC173 SC1 WG11 Wheelchair Seating, and lead for the Task Group that produced BS ISO 16840-10.	Information on wheelchair cushions and other upholstered medical devices	17/08/2021

In the structured interviews, the industry experts were invited to: comment on the product list; to educate us on the safety regulations pertaining to the different products; and to describe typical product constructions, including materials and FRs employed. The interview questions are shown in Appendix 20.

4.2 Product characterisation and scoring of their fire and chemical risks

The focus of the product characterisation element of this research was confined to those characteristics critical to the risk matrix. Particular effort was made to adequately define the furniture product types as well as assess the variability within them, based on products currently being placed on the market.

Comprehensive academic and grey literature to support this exercise does not exist and hence the research team had to establish, through desk-based research (mostly of retailer websites) and the industry expert input, a working understanding of each furniture product type for the benefit of this research.

Literature identified that did provide some partial information related to this research includes the FIRA guide to the FFFSRs[5] providing an overview of how flammability regulations are applied to domestic furniture and clarity on what is and isn't in scope, and the guide published by the government department responsible[73] providing a furniture product type specific guide to following FFFSRs for producers and suppliers.

To support the scoring exercise, we identified a diverse range of items from each furniture product type and identified the smallest, least complex item and the largest, most complex item. These are referred to as the low and high-risk product variants in the derivation of the risk matrix. Using pet beds as an example, the approach within the furniture safety matrix to assessing the fire risk and CFR exposure risk is described below (Table 3).

Table 3 Range of pet beds available, as a function of size and complexity (images not to scale)

Smallest, least complex item → → → → → → → → → Largest, most complex item				
Small breed flat bed	Small breed rounded bed with rim	Medium breed more-angular bed with rim	Large breed more-angular bed with rim	Large breed round dog bed with hood
				

The extremes of smallest, least complex and largest, most complex items were then scored based on the dimensions of the fire and exposure risk matrices. The only quantitative characterisation of the furniture relevant to the risk scoring was the combustible volume (as a proxy for fire severity if ignited) and surface area (as a proxy for contact area for exposure). Combustible *volume* was selected rather than *mass* as the parameter most likely to correlate to heat release rate and hence fire growth. A low-density filling will ignite and burn more quickly than a high-density filling, although the total heat release of the latter may be greater. These calculations were done in the most part by assuming the products were a series of basic geometric shapes (rectangles, ellipses, cylinders etc.). Non-upholstered, solid wood components (such as bed slats or cot rails) were excluded from the combustible volume. For extremely complex shapes, as found in baby products like pushchairs, we instead visually estimated the combustible volume by considering how many pillows (or what fraction of a pillow) of combustible content was in the items. Scoring the furniture on the other dimensions of the risk matrix was based on aggregating judgements of team members, validated by external stakeholders, as described in Sections 4.5.4 and 5.6.4.

4.3 Scoping and developing the evidence base on domestic upholstered products for populating the furniture safety matrix

4.3.1 Determination of scope of products for investigation.

The product scope provides a comprehensive list of small domestic upholstered furniture products whose potential hazards are to be assessed in the furniture safety matrix. The starting point was the list proposed in the BEIS-OPSS Invitation to Quote document (ITQ), which was expanded to include similar products, refined with input from the BEIS-OPSS policy team and then sense-checked with expert stakeholders. Table 4 shows the original product list and the proposed product list within a number of product groupings.

Table 4 Product grouping of original and proposed furniture product types.

Product Grouping	Original ITQ list	Proposed list
Upholstered bed component grouping	Headboard Footboard	1.Headboard 2.Footboard 3.Side-rails 4.Upholstered bed bases 5.Divans
Cushion and pillow grouping	Scatter cushions Children's light up cushions Seat Pads (example, for kitchen chairs, for wheelchairs) Pillows	6.Scatter cushions 7. Children's light up cushions 8. Seat Pads (example, for kitchen chair) 9. Pillows 10. Floor cushions 11. Bean bags
Seating and footstool grouping		12. Padded stools/ Footstools / Ottomans 13. Loose covers and stretch covers for sofas/upholstered armchairs
Child transportation grouping	Prams / Push Chairs Cycle Child Trailers and Strollers Car Seat	14. Prams / Push Chairs 15. Cycle Child Trailers and Strollers 16. Car Seats
Baby sleep product grouping	Baby mattress Cots/Cribs Baby travel cots/ Carry cots/ Carry cribs Moses baskets Baby nests	17. Baby mattress (inc. cot bed mattresses 18. Cots/Cribs 19. Carry cots/ Carry cribs/ Moses baskets 20. Baby travel cots / Playpens 21. Baby nests
Products for babies to nap in/sit on grouping	Bouncing cradles Baby rockers Baby bouncer Baby Swing Baby walking frames Baby highchairs Chair harnesses	22. Baby products supplied with an upholstered seat, harness or other support (including bouncing cradles, baby rockers, baby bouncer, baby swing, baby walking frames, baby highchairs, door bouncers, travel highchairs, booster seats, baby carriers) 23. Separately supplied upholstered products for baby/child seating comfort (including inserts/ cushions/ supports)

Products for babies to play on/in grouping	Play mats Playpens	24. Play mats 25 (a). Baby changing mats 25(b). Dresser units (with built in changing mats)
Pet furniture grouping	Pet beds	26. Pet beds
Outdoor furniture grouping	Outdoor furniture	27. Outdoor furniture 28. Upholstered items for use with outdoor furniture, but not necessarily supplied with outdoor furniture
Assistive care products		29. Upholstered supports or living aids (including wedges, supports, rails, wheelchair seatpads and similar products). Also referred to as living aids.

Feedback from the industry stakeholders interviewed was that the list of products (in their respective areas) was comprehensive and would support product definition and characterisation within the scope of the current research.

It was flagged that certain products, such as stretch and loose and covers and side-rails, are relatively unfashionable at the moment but that this shouldn't exclude them from consideration. A trend towards increased upholstery in certain baby products, namely baby rockers and gliders, was also mentioned.

The need for clarity as to how product types that are usually used in association with other product types are handled in the risk assessment was flagged by the stakeholder group. For example, in the cushion and pillow grouping, some product types (e.g. scatter cushions and pillows) are generally used in conjunction with larger upholstered furniture, whilst floor cushions and bean bags are not. In the risk model, product types were assumed to present independent fire risks, i.e. the possibility that one item may be ignited and cause another item to ignite was not modelled. The exception was loose and stretch covers on sofas and armchairs, that were assumed to only be used in conjunction with an item, and effectively inherit the risk of the item on which they are used. [i] This is a limitation in the model, partly due to the scope of the review whereby we were required to treat items separately as they are under the FFFRs (e.g. headboards and bed bases), and partly due to the challenges of modelling risk dependencies between items exceeding what could be achieved with the resources and time-frame associated with the project.

Interviewed stakeholders also supported our understanding of other standards and regulations related to the products in scope, see Table 5. Some products on the list were also flagged as not being in scope of the FFFSRS, citing Department of Trade and Industry (DTI) guidance, and these are highlighted in *italics* in the table. There was also a suggestion that it was industry practice that cushions smaller than 30 cm x 30 cm (i.e. small enough that it would be uncomfortable to sit on) were considered out of scope of the regulations though there is no reference to this in the official guidance.

[i] More detail on the methodology used to populate the fire safety risk matrix can be found in Section 5.5. The majority of the considerations related to how product types are used and in conjunction with what else are captured in the narrative comments the evaluators produced alongside scoring the product types on the Likert scale for the various matrix domains.

Table 5 Other safety standards, apart from the Furniture and Furnishings (Fire)(Safety) Regulations (FFFSR) that apply to the products in scope. Items that industry stakeholders indicated as being currently outside the scope of the FFFSR are indicated in red.

Product List	Safety regulations and standards (excl. FFFSR)	Other consideration
1. Headboard 2. Footboard 3. Side-rails 4. Upholstered bed bases 5. Divans	4 & 5 BS 7177: 2008 + A1:2011, BS EN 1725:1998	3. Decorative side-rails aren't a common separately marketed product (on the current market). Safety side rails (which would fall into the assistive care product category aren't in scope here
6. Scatter cushions 7. Children's light up cushions 8. Seat Pads (example, for kitchen chair) 9. Pillows 10. Floor cushions 11. Bean bags	7. (Assuming they're 'child appealing') are in scope of BS EN 71-1: 2014+A1:2018; BS EN 71-2:2020; BS EN 71-3:2019+A1:2021; and BS EN IEC 62115:2020+A11:2020	11. Covers similar to loose/stretch covers
12. Padded stools/ Footstools / Ottomans 13. Loose covers and stretch covers for sofas/upholstered armchairs	12 BS EN 12520:2015	12. Can be bought as part of suite (with armchair, sofa etc.). Means FR fabric would in practice be used on smaller footstool-type items, whatever the regulatory status, if required for the larger items. 13. Loose covers are supplied with a product (i.e. product specific) and stretch covers supplied separately and can be used on multiple products.
14. Prams / Push Chairs 15. *Cycle Child Trailers* and Strollers 16. Car Seat	14. BS EN 1888-1:2018 and BS EN1888-2:2018 15. BS EN 1888-1:2018 and BS EN1888-2:2018 16. ECE R44/04 and R129 (contains toxicity and flammability requirements)	14. Pram for child <15kg, pushchair between 15kg and 22kg 15. Cycle trailers are not in scope of the FFFSR regulations 16. FFFSRs regulations only apply to the size 0 car seats, those for infants up to 1 year with a handle (for carrying into the house).
17. Baby mattress (inc. cot bed mattresses 18. Cots/Cribs 19. Carry cots/ Carry cribs/ Moses baskets 20. Baby travel cots / Playpens 21. Baby nests	17. BS EN 16890:2017 18. BS EN 716:2017 19. BS EN 1466:2014 20. BS EN 716:2017 (Travel cots) and BS EN 12227:2010 (Playpens)	20. Multi-functional products must meet the standards of all products they function as. 21. Unsure of definition as term may have referred to a different product in 1988 than it does today

22. Baby products supplied with an upholstered seat, harness or other support (including bouncing cradles, baby rockers and gliders, baby bouncer, baby swing, baby walking frames, baby highchairs, *door bouncers*, travel highchairs, booster seats, *baby carriers*) *23. Separately supplied upholstered products for baby/child seating comfort (including inserts/ cushions/ supports)*	22. BS EN 12790:2009 (Bouncing cradles, baby rockers, baby bouncers) BS EN 16232:2013+A1:2018 (infant swing) BS EN 1273:2020 (baby walking frames) BS EN 14988:2017+A1:2020 (highchairs) BS EN 16120:2012+A2:2016 (chair mounted booster seats and travel highchairs) BS EN 14036:2003 (baby bouncers) BS EN 13209-2:2015 (baby carriers)	22. Baby gliders are another term for baby rocker. Table mounted highchairs is a better, more specific, term for travel highchair. When products have a discrete 'child appealing' element such as a toy bar on a Baby carriers are designed for use outside the house 23. These separately supplied products are currently not in scope of the FFFSRs regulations
24. Play mat *25. Baby changing mats* 25(b). *Dresser units (with built in changing mats)*	24. (Assuming they're 'child appealing') are in scope of BS EN 71-1: 2014+A1:2018; BS EN 71-2:2020; and BS EN 71-3:2019+A1:2021 BS EN 12221:2008+A1:2013. Changing pads are only covered by this standard when they form a part of the changing unit.	25. Similar to 23 (separately supplied upholstered…), baby changing mats (or pads) are outside the scope of the regulation
26. *Pet beds*	26. Required to comply with GPSR	
27. Outdoor furniture 28. Upholstered items for use with outdoor furniture, but not necessarily supplied with outdoor furniture	27 BS EN 581-1: : 2017, BS EN 581-2:2015	27. FFFSRs regulation does not apply to products which can't conceivably be brought inside for use or storage.
29. Upholstered supports or living aids (including wedges, supports, rails, wheelchair seatpads and similar products)	29. Medical Devices Regulations 2002 apply to some products (such as pressure relief products)	29. Medical Device Regulation (clause 7.1 of Annex 1) states "general requirement that, in the design of the medical device, particular attention must be paid to "the choice of materials used particularly as regards to toxicity and, where appropriate, flammability".

4.3.2 Product grouping profiles

In this section we set out the knowledge we have on the products in scope. Products are grouped into those with similar use profiles.

4.3.2.1 Upholstered bed component grouping

Table 6 Definitions of upholstered bed component items

Furniture product types	Working definition
1. Headboards	An upright board, at the end of a bed where you lay your head, which can be attached to the bed, but not to a wall.
2. Footboards	An upright board at the foot of a bed
3. Side-rails	Upright board(s) at the side of a bed
4. Upholstered bed bases	Upholstered bed frames with a slatted surface for the mattress, which may comprise of some or all of the following: built in headboard, footboard and side rails. Can have storage drawers or 'ottoman-style' storage within it. Normally supplied for *in situ* assembly.
5. Divans	Upholstered bed base with a flat or sprung surface for a mattress. Can have storage drawers or 'ottoman-style' storage within it. Normally supplied fully assembled

Insight from desk-based research and industry expert interviews

The fire safety of side-rails, upholstered bed bases and divans is controlled by GPSR, whilst that of their fillings must meet FFFSRs requirements. Headboards and footboards, of which both faces are considered to be 'visible' fabric, are required to meet the full requirements of the FFFSRs[ii].

In practice this means that, in general, cover fabrics used for headboards and footboards are treated with chemical flame retardant back-coatings (if not made from inherently flame retardant fabrics) whilst the cover fabric on the sides of divan bases is not. The non-slip material on the top of the divan, onto which the mattress is generally placed, is also flame retarded as it could potentially be used as a sleeping surface[iii].

The most common chemical treatments used to flame retard upholstered bed component cover fabrics are brominated flame retardants and organophosphate FRs, which are applied to the reverse side of the fabric at loadings of between 30-60 grams per square meter. Red phosphorus treatments are also applied to the reverse side of fabrics but, because the red colour leaches through, it is only suitable for very dark coloured fabrics and is not widely used. Expandable graphite can be used at much lower loadings, approximately 7 grams per square metre, but being an intumescent CFR it may need to be used on the front-face of the fabric which is rarely suitable for upholstery covers in high-wear applications.

Standard filling materials used in upholstered bed components are flexible polyurethane (PU) foams and polyester wadding. Natural fibres and latex foams can be used but are much less common. The PU foams are typically 20-30 kg m^{-3} combustion modified high resilience (CMHR) foams containing between 5-10% by weight of TCIPP and/or melamine. Generally no additional flame retardant chemical treatments are required for polyester fillings.

[ii] Excluded from the scope of this research, but of relevance as they could be used in the same capacity as the above products, are sofa-beds, futons and other convertible furniture.
[iii] Though this is less likely than in the 1980s as the market share of sprung divans has reduced since then.

Side-rails are not, in general, sold separately. Though still a common term in the furniture industry, the understanding of 'side-rail' by the general public may have evolved since the 1980s as many of the products referred to using that term are now safety rails to prevent very young and very old people falling out of bed.

4.3.2.2 Cushion and pillow grouping

Table 7 Definitions of cushion and pillow group items

Furniture product types	Working definition
6. Scatter cushions	Cushion with dimensions smaller than 60 cm x 60 cm x nominal product thickness
7. Children's light-up cushions	Cushion containing battery operated LED lights
8. Seat pads	Pad for use on non-upholstered chair seats
9. Pillows	Item used on a bed to support a sleeper's head
10. Floor cushions	Cushion with dimensions greater than 60 cm x 60 cm x nominal product thickness
11. Bean bags	A soft seat consisting of a large bag made from fabric or another upholstery material, filled with discrete bean-sized beads, and usually greater than 60 cm x 60 cm.

Insight from desk-based research and industry expert interviews

The FFFSRs only applies to the fillings used in pillows, scatter cushions and seat pads, not the overall products.[iv] One interviewed expert indicated that it is standard industry practice to exclude scatter cushions smaller than 30cm x 30cm from the testing required by FFFSRs for cushions. However, official (DTI) guidance on the FFFSRs makes no reference to this exclusion. As only fillings are in scope of FFFSRs for these products, decorative covers for scatter cushions and seat pads, including covers for these items which are sold separately are out of scope. However, for floor cushions and bean bags, for which there is no upper-size limit given in the guidance documents, the entire products are required to meet the requirements of the FFFSRs.

Excluding bean bags, the most common filling material used in these products is polyester wadding. This can either be produced from solid or hollow (for extra heat insulation properties) fibres carded and thermally bonded together to produce fillings with typical densities between 15 kg m^{-3} and 25 kg m^{-3}. Polyester's propensity to melt away from heat sources means that additional chemical flame retardant treatments are generally not required.

Viscoelastic polyurethane foams, more commonly known as 'memory foam', can be used in pillows and are sometimes marketed on their orthopaedic benefits. These foam pillows are typically 2.5 times heavier than standard polyester-fibre filled varieties with filling densities between 50 kg m^{-3} and 60 kg m^{-3}.

- Other less common filling materials for these products include down, foam crumb, cotton wadding and wool. For reference, over 90% of pillows currently placed on the market are polyester filled with the remainder being mostly down and memory foam.

[iv] If scatter cushions are sold as part of an item of furniture they would need to be fully compliant with the regulations.

- The most common filling for bean bags is expanded polystyrene beads, though alternatives include polypropylene beads, foam crumb, dried beans, buckwheat husks, and bio-derived, compostable plastics[v].
- Whilst not in scope of this research we noted the existence of foam- or rubber-filled floor mats, sometimes referred to as 'anti-fatigue mats or 'foam rugs' which are marketed for use in kitchens to relieve tiredness when standing for extended periods of time.

4.3.2.3 Seating and footstool grouping

Table 8 Definitions of seating and footstool items

Furniture product types	Working definition
12. Padded stools/ Footstools / Ottomans	Small upholstered items without arms or backs, that can be used to sit on or rest your feet or other items on. Can contain a solid frame with/without internal storage or could be more like a large 'pouffe'[vi]
13. Loose covers and stretch covers for sofas/upholstered armchairs	Covers for upholstered items that are designed to be placed on top of an existing finished piece of furniture which is already fitted with a permanent cover[vii]. Generally, these are produced by a producer other than the manufacturer of the furniture. Stretch covers are those which have elasticity meeting the specifications of BS 4723.

Insight from desk-based research and industry expert interviews

According to the FFFSRs padded stools, footstools and ottomans must pass the appropriate cigarette test, contain filling material which passes the appropriate test and has cover fabric that passes the appropriate match test. The FFFSRs testing required for loose and stretch covers differs in that the former must comply with the match test over standard foam whilst the latter is tested over combustion modified foam.

For solid-framed padded stools, footstools and ottomans; the materials used are similar to that found in larger upholstered products such as armchairs and sofas. If sold as part of a furniture suite the fabric material for these items would be dictated by that used on the larger items.[viii] Industry experts also indicated that the density of foam used in these items is typically lower than used for the seats of armchairs and sofas, circa 20-25 kg/m^3, as they are not intended for prolonged sitting.

Loose and stretch covers differ from permanent covers, either supplied with or separately from the furniture item they are produced for, in that they are designed to be fitted over existing covers and are made by a producer other than the manufacturer of the furniture item.

Industry sources suggested that there was some confusion in the general public around whether and how upholstered furniture covers, the majority of which come with a zip to allow the filling to be easily put in during manufacture, can be washed or cleaned. They are usually

[v] https://bigbeanbagcompany.com/ethos/?v=79cba1185463
[vi] Also spelled 'pouf' and defined in the Collins English Dictionary as 'a large solid cushion' and the Oxford English Dictionary as 'a cushioned footstool or low seat with no back'.
[vii] As per FIRA guidance document
[viii] i.e. if flame retardant use on covers was no longer required for these products, they still might be used if they were still required for sofas and armchairs.

labelled as being non-washable though this may be ignored or overlooked.[ix] Though CFR fabric treatments generally undergo a water soak prior to the match test, the impact of domestic washing machine cycles on the fire protection they can provide is unknown, as is the extent to which various means of cover washing are used in homes.

4.3.2.4 Child transportation grouping

Table 9 Definitions of child transportation items

Furniture product types	Working definition
14. Prams / Push Chairs	Prams are wheeled conveyances for children under 15 kg, and pushchairs for children over 15 kg.
15. Cycle Child Trailers and Strollers	Stroller is a common term, often used along with buggy and baby-carriage' for pushchair. However, for this research we are taking it to mean push-along tricycle, scooter or toy type contraptions. Cycle child trailers are detachable trailers, containing dedicated seats for children, that can be pulled by bicycles, and can sometimes double as pushchairs.
16. Car Seats	The only child car seats of relevance to this research are group 0 and 0+ car seats intended for small infants (up to 85 cm tall). This is because these are the car seats with a handle for carrying them in and out of dwellings. Car seats for larger infants and booster seats for children would be expected to remain in the vehicle.

Insight from desk-based research and industry expert interviews

The products listed above, and other items that perform any of the same functions as those products (given that it is common for baby-products to be multi-functional), must meet the same requirements for domestic upholstered furniture. The small size of the upholstered components, which can be as minimal as the padding around a safety restraint, poses a technical challenge to testing the materials and products.

The most common upholstery filling materials used in these products are polyurethane foam, particularly in car seats, and polyester wadding. Typical filling densities are 20-25 kg m^{-3}. Polyester and other synthetic fibre blends are common cover materials along with PVC and polyurethanes for applications where wipeable surfaces are desired. Natural fibres (such as wool and silk) are not used widely in these products because of their cost, durability and design limitations. The weight of fabrics used in baby products, and prams and pushchairs in particular, is typically lighter (in grams per square metre) than for general domestic upholstery applications. As such the CFR loading levels are higher, to prevent the fire penetrating through to the filling, which, according to industry experts, has a detrimental effect on fabric feel.

4.3.2.5 Baby sleep product grouping

Table 10 Definitions of baby sleep items

Furniture product types	Working definition
17. Baby mattress (including cot bed mattresses)	Baby mattresses 120 cm x 60 cm or less. Cot bed mattresses are greater than 120 cm x 60 cm but less than or equal to 140 cm x 70 cm
18. Cots/Cribs	Bed for infant with legs/base to raise it off the floor which fits mattress no larger than 120 cm x 60 cm.

[ix] Furniture manufacturers are aware of this from questions they receive from customers. Additional evidence of this confusion can be found on internet forums such as: https://www.mumsnet.com/Talk/housekeeping/3058996-Machine-washing-sofa-cushion-covers

19. Carry cots/ Carry cribs/ Moses baskets	Bed for infant without legs/base to raise it off the floor which fits mattress no larger than 120 cm x 60 cm. Usually comes with handles to make carrying/moving the item easier.
20. Baby travel cots / Playpens	Travel cots can be designed to double as playpens and vice versa. These are typically items with a padded base and frame to support netting or other material designed to prevent young children from getting out without assistance from an adult. Some play mats with raised edges (which children who can crawl/walk could escape from unaided) can also be marketed as playpens.
21. Baby nests	An infant sleep positioner which is a mat for babies to sleep on with bolsters, raised support or pillows attached[x]. Sometimes also called 'pods'

Insight from desk-based research and industry expert interviews

Mattresses intended for baby and infant use are required to meet the same requirements as mattresses for adults, i.e. that only the filling materials must meet the requirements set out in the FFFSRs, while the fire safety of the complete product is controlled via the General Product Safety Regulation (GPSR). Any mattress toppers for cots or cribs are also deemed to be mattresses, for the purpose of regulating their fire safety.

Any upholstered parts or items supplied with furniture for babies and infants to sleep in (including cots, cribs, carry cots, carry cribs, moses baskets and travel cots) must meet FFFSRs requirements. This includes mattresses. Whilst all the above products, as well as playpens, must meet the full testing requirements set out by the FFFSRs there is an exemption made for baby nests, possibly given their small size, excluding them from the match resistance test.

Mattresses for babies and infants are different to those for older children and adults in that they are designed to support significantly less weight. As such they use less dense fillings, lower spring tensions (in sprung mattresses) and much thinner constructions. Cot mattresses generally weigh 4-6 kg compared to adult mattresses that weigh an average of 25 kg. Nevertheless, they can contain all the same materials as found in larger mattresses, with polyurethanes and polyester fillings being most common and polyester fabrics also making up most of the mattress 'ticking'. Note that waterproof mattress protectors are routinely used with these products.

Cots and cribs are usually of solid wood constructions in a traditional design with carry cots, carry cribs and moses baskets also usually containing minimal upholstery, excusing the mattress. There are ornate, heavily upholstered items on the market however these are relatively rare.

Baby nests are not recommended for use because of a potential increased risk of accidental suffocation, however they are still a widely used product. [xi] They, along with carry cots, carry cribs and moses baskets are easily movable and can be used in any room of the house and placed on floors, hard surfaces (including kitchen counters) and soft surfaces (including beds and sofas).

[x] Industry representatives indicated that in the 1980s these sleep positioning products did not exist on the market and that the term, which is used in guidance documents produced to support interpretation of the FFFSR, instead refers to products which are now generally called 'foot muffs' or 'cosy toes' (sleeping bag like inserts for use in pushchairs and prams).

[xi] https://www.lullabytrust.org.uk/the-lullaby-trust-issues-warning-about-some-popular-baby-sleeping-products-sold-in-high-street-stores/

4.3.2.6 Products for babies to nap in/sit on grouping

Table 11 Definitions of items for babies to nap in/sit on

Furniture product types	Working definition
22. Baby products supplied with an upholstered seat, harness or other support (including bouncing cradles, baby rockers, baby bouncer, baby swing, baby walking frames, baby highchairs, door bouncers, travel highchairs, booster seats, baby carriers)	Items designed for babies and small children to nap in and/or sit on which contain a seat, harness and/or other restraint from which the child (at the age for which the products are designed) is unable to get out of without assistance from an adult. These products (or elements of these products) may or may not have play value (i.e. are child appealing) and, as such, may or may not be covered by the toy safety regulations.
23. Separately supplied upholstered products for baby/child seating comfort (including inserts/ cushions/ supports)	Small cushions (often irregularly shaped) to support, or provide additional support and/or comfort, for babies and small children in larger products including those in product categories N, O, P and W.

Insight from desk-based research and industry expert interviews

Industry experts and official (DTI) guidance to interpreting the FFFSRs both confirmed that a number of products in this group are in fact outside the scope of the FFFSRs. This includes:

- Baby bouncers that can be suspended from doorways or similar
- Baby carriers, slings and rucksacks to carry babies in (which are designed to be worn outdoors)
- Upholstered liners or inserts that are supplied separately to main baby napping/sitting product.

For all other products the FFFSRs requirements apply in full, meaning that fillings and cover fabrics must meet the required flammability tests.

These products in which babies nap in or sit on have been grouped because they are similar in that they can contain an upholstered seat, harness or support. They may also contain other upholstered elements, often some padding around a hard component, added for safety or aesthetic reasons. In general, the level of upholstery is minimal in these products, though industry experts did note there was a trend to higher levels of upholstery in baby gliders and rockers.

Some upholstered furniture products also have to meet requirements of other product sector safety legislation. This includes, but is not limited to, the Toy Safety Regulations 2011 for certain child appealing items and the Supply of Machinery (Safety) Regulations 2008 where products contain electronic components or motors.

4.3.2.7 Products for babies to play on/in grouping

Table 12 Definitions of items for babies to play on/in

Furniture product types	Working definition
24. Play mats	Soft mats intended for babies and small children to play on.
25. Baby changing mats	A mat on which a baby or young child is placed to have their nappy changed
25(b). Dresser units (with built in changing mats)	An item of furniture (can include shelves, drawers, rails, hooks or none of the above) with a built-in (non-removable) mat on which a baby or young child is placed to have their nappy changed.

Insight from desk-based research and industry expert interviews

Industry experts and official (DTI) guidance to interpreting the FFFSRs both confirmed that all the products in this group are in fact outside the scope of the FFFSRs. This includes:

- Play mats
- Baby changing mats
- Dresser units

4.3.2.8 Pet furniture grouping

Table 13 Definitions of pet furniture items

Furniture product types	Working definition
26. Pet beds	Product intended for pet to sleep in or on

Insight from desk-based research and industry expert interviews

We understand that pet beds are outside the scope of the FFFSRs, though their overall safety is still controlled via GPSR. We note that there is still some uncertainty regarding this, with some suggesting that they should be considered as floor cushions given that they are, in principle, large enough to sit on.[xii]

Pet beds are like floor cushions in the filling materials they use, with polyester and foams most common. Their cover fabrics are typically heavier-duty however, and often water repellent and washable (to reduce build-up of odours).

4.3.2.9 Outdoor furniture grouping

Table 14 Definitions of outdoor furniture items

Furniture product types	Working definition
27. Outdoor furniture	Furniture intended for garden or other outdoor use which could conceivably be brought inside a dwelling for use or storage.
28. Upholstered items for use with outdoor furniture, but not necessarily supplied with outdoor furniture	Cushions and other upholstered items intended for garden or other outdoor use which could conceivably be brought inside a dwelling for use or storage.

Insight from desk-based research and industry expert interviews

Upholstered outdoor furniture, or components thereof, that can conceivably be brought inside a dwelling must meet the same requirements as for domestic upholstered furniture. This definition includes the vast majority of upholstered outdoor furniture items, with only those that wouldn't fit through a double door potentially excluded.

Outdoor furniture upholstery predominantly uses reticulated flexible polyurethane foam fillings, a type of foam with a very open pore structure that allows water and moisture to pass right through, thus preventing the foam from degrading and the build-up of mildew. Porosity is specified in pores per square inch (ppi) with at least 30 ppi recommended for outdoor furniture use. Typical densities are 20-30 kg/m^3.

Cover materials used in outdoor furniture are generally more durable and hard-wearing than those designed for internal upholstery use. They are often water-repellent and have UV light,

[xii] https://www.satra.com/spotlight/article.php?id=451

mildew and micro-organism resistant properties to increase their durability. PVC and polyurethane coatings and treatments are common.

4.3.2.10 Assistive care products (Living aids)

Table 15 Definitions of assistive care items

Furniture product types	Working definition
29. Upholstered supports or living aids (including wedges, supports, rails, wheelchair seatpads and similar products)	Upholstered medical devices or 'medical device like' products which are defined as any upholstered products with demonstrable ability to alleviate pain or improve health. Products very similar in appearance to upholstered medical devices but that aren't certified as such themselves, are also in scope.

Insight from desk-based research and industry expert interviews

Though there is advice to the effect that heavily upholstered wheelchairs intended for use in domestic environments be treated as upholstered chairs and thus meet all relevant requirements of the FFFSRs, in reality most upholstered medical devices fall outside the scope of the FFFSRs.

Nevertheless, it is standard industry practice, according to an industry expert, that foam and composite fillings for wheelchair cushions and other upholstered medical devices are compliant with the FFFSRs. The composites used include gels, elastomers and air, to provide pressure relief and breathability, which do present challenges for the fire testing.

Medical mattresses are upholstered medical products, however we haven't included them in our definition of upholstered medical products as they are, in practice, part of a continuum of products ranging from domestic to medical mattresses with no clear way to differentiate between them.

5. Furniture Fire Safety Matrix: Methodology

5.1 Summary of overall approach

Objective: To characterise fire risks and potential for fire retardant exposure presented by categories of small upholstered furnishings in the form of a risk matrix. The matrix should allow furniture product types to be distinguished according to risk and exposure profile.

Method: We conducted a concept mapping exercise, based on representative literature supplemented by expert input, to systematically identify factors that affect fire risk and exposure to fire retardants (FRs) in furniture while in use. This created a concept network from which a fire risk and FR exposure model could be derived. We then surveyed the literature to gather empirical evidence relevant to quantifying elements of the concept network that differentiate fire risk and FR exposure in furniture product types. Due to a lack of such data, we selected fire risk and FR exposure concepts from the network that could be integrated into a risk model, measured qualitatively, and allow furniture product types to be positioned relative to each other in an overall risk/exposure matrix.

Results: The matrix successfully differentiates items of furniture in terms of relative fire risk and FR exposure profile. In particular, it appears that baby products have a different combined risk and exposure profile to most of the other furniture product types included in the study. The lack of empirical evidence relating to furniture fire safety other than product flammability, and the way the project was parameterised to focus on furniture product types, means absolute measures of fire risk cannot be provided.

5.2 Methodology

5.3 Summary of the methodology

We conducted a purposive literature review to provide a comprehensive account of potential furniture fire risk, chemical fire retardant exposure factors, and how they are related to each other. We supplemented this review with expert input to identify risk- or exposure-relevant concepts that are not represented in the academic literature. We present the results of this exercise in the form of a concept map, that provides a comprehensive representation of contemporary understanding of furniture fire risk and FR exposure factors, from which a comprehensive fire risk and exposure model can be derived.

We then analysed the full furniture fire safety literature to assess the potential level of empirical support for the role of each concept in the network to overall fire risk and FR exposure. In general, there was a lack of empirical data for the following: about the involvement of furniture product types in fires; the extent to which specific features of furniture product types contribute to fire risk (such as location, use, and design); and the extent to which categories of furniture contribute to FR exposure. Overall, there were insufficient empirical data to quantify most of the risk and exposure factors identified in the concept network. We therefore had to develop an alternative approach to characterising fire risk and potential for FR exposure associated with furniture.

To do this, we selected from the concept model risk domains that both differentiate risk in furniture product types and can be reasonably quantified despite a lack of empirical data. Some domains could be measured (e.g. upholstered volume). For other domains, we used qualitative judgements for furniture characteristics based on high-risk and low-risk examples of furniture product types. We then used simple numerical models with minimum assumptions to calculate overall fire risk and exposure potential scores for each furniture product type. We plotted these on a scatter chart to show relative fire risk and FR exposure potential of one item compared to another. While not presenting absolute risk, this approach allowed us to differentiate risk between furniture product types in spite of a lack of empirical data.

This is useful for risk modelling because if the level of risk posed by particular furniture type (e.g. an armchair) is considered to be a risk benchmark, then other types determined to pose approximately equivalent risk can be subject to similar risk management measures as the type in question. Likewise, those posing less risk can potentially be subject to less stringent measures, and those posing greater risk can potentially be subject to more stringent measures.

5.4 Literature review and concept modelling

In order to develop a comprehensive list of factors which affect fire risk and potential for exposure to fire retardants presented by small upholstered furniture product types, we conducted a review of the published literature on furniture fire safety, supplemented by expert analysis to identify fire risk and exposure factors that are not represented in the published evidence base. Once a comprehensive list of risk and exposure concepts had been created, the concepts were organised into a logical hierarchy that summarises contemporary understanding of how small upholstered furniture product types can pose a fire risk or be a source of exposure to fire retardants.

5.4.1 Literature search

To conduct the search, we used the Scopus database due to its broad coverage of the technical fire safety literature and journals.[xiii] The search was supplemented by reviews identified as potentially relevant by expert advisors to BEIS-OPSS. Documents were included in the literature sample if they were about the fire behaviour of furniture (i.e. involvement and propagation), or about furniture as a source of exposure to fire retardants, were published in English, and were available in a format that could be imported into our document analysis environment (i.e. in electronic format and not protected by Digital Rights Management software).

The eligible documents were limited to reviews because the objective was to map what experts, via their written work, identify as important furniture fire safety risk factors. The breadth and density of these concepts is likely to be much higher in reviews rather than reports of experimental studies; since the reviews cover the experimental studies, it is reasonable to infer that most of the concepts in the studies should be mentioned in at least one review.

The search returned 111 results, of which 50 documents were determined to be eligible according to topic. 4 results were not in English and 24 were not available as electronic documents (5 were secured via inter-library loans but digital rights management protections meant they could not be imported into the document analysis environment). 8 documents were added from a list provided by BEIS-OPSS (we excluded book-length treatments for time reasons). Finally, we added the EN ISO 13943-2017 fire vocabulary document, in case it proved useful for using standardised vocabulary in the risk matrix. This yielded a total of 31 documents. The list of included documents is in Appendix 1. (Note that one document turned out to be in Japanese with an English title and abstract, so we annotated the abstract.)

[xiii] The following search string was used, intended to cover furniture and fire concepts, limiting results to reviews: TITLE-ABS-KEY ((furniture OR furnishing*) AND (flam* OR fire)) AND (LIMIT-TO (DOCTYPE , "re")).

5.4.2 Concept modelling

The purpose of the concept modelling process was to systematically identify all factors that are currently considered to be modifiers of fire risk in furniture, with a secondary objective of also identifying potential modifiers of exposure to FRs from the domestic use of furniture. The output of the process is a comprehensive list of furniture fire safety and fire retardant exposure concepts and the logical relationships between them. These can be represented and analysed as a graphical concept map (a set of nodes connected by arcs).

Concept mapping was conducted via detailed analysis of the literature sample (where fire risks and FR exposure are discussed in written form) combined with expert input, to allow knowledge of risk factors that are not discussed in the academic record to be incorporated into the overall concept model. The process is iterative, with the list of concepts being built out then refined, and the relationships between the concepts identified and refined, in a reflective process that is repeated multiple times until a model of sufficient validity for the analysis task has been developed. To illustrate the output of this process, Figure 5 shows a segment of the final concept network, characterising how open flames are a potential ignition source for upholstered furnishings.

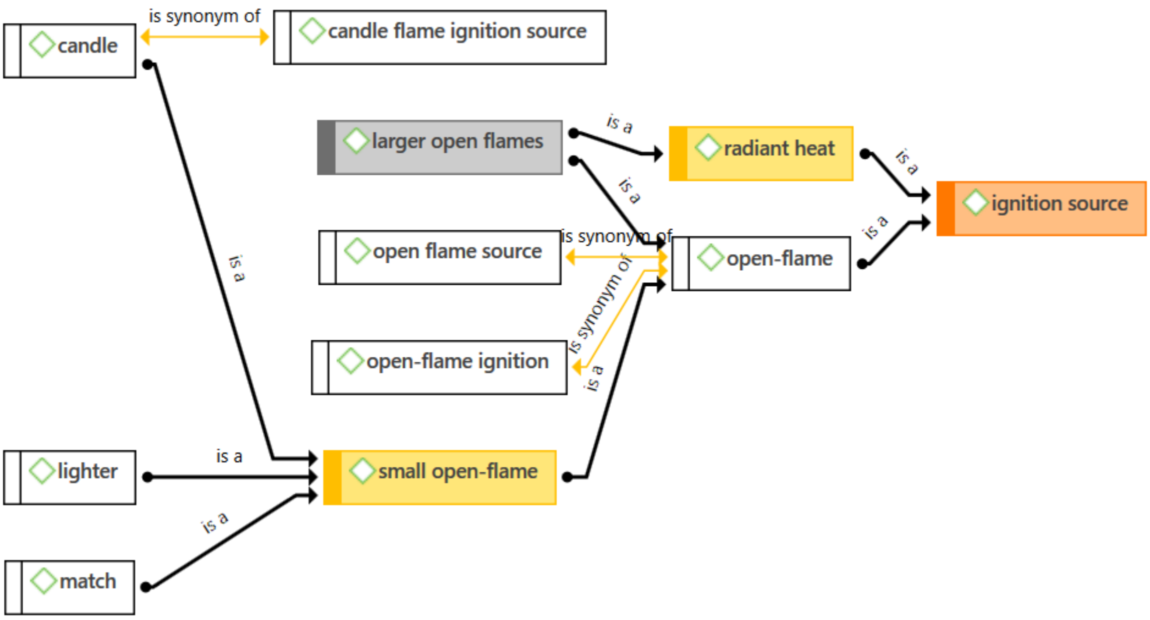
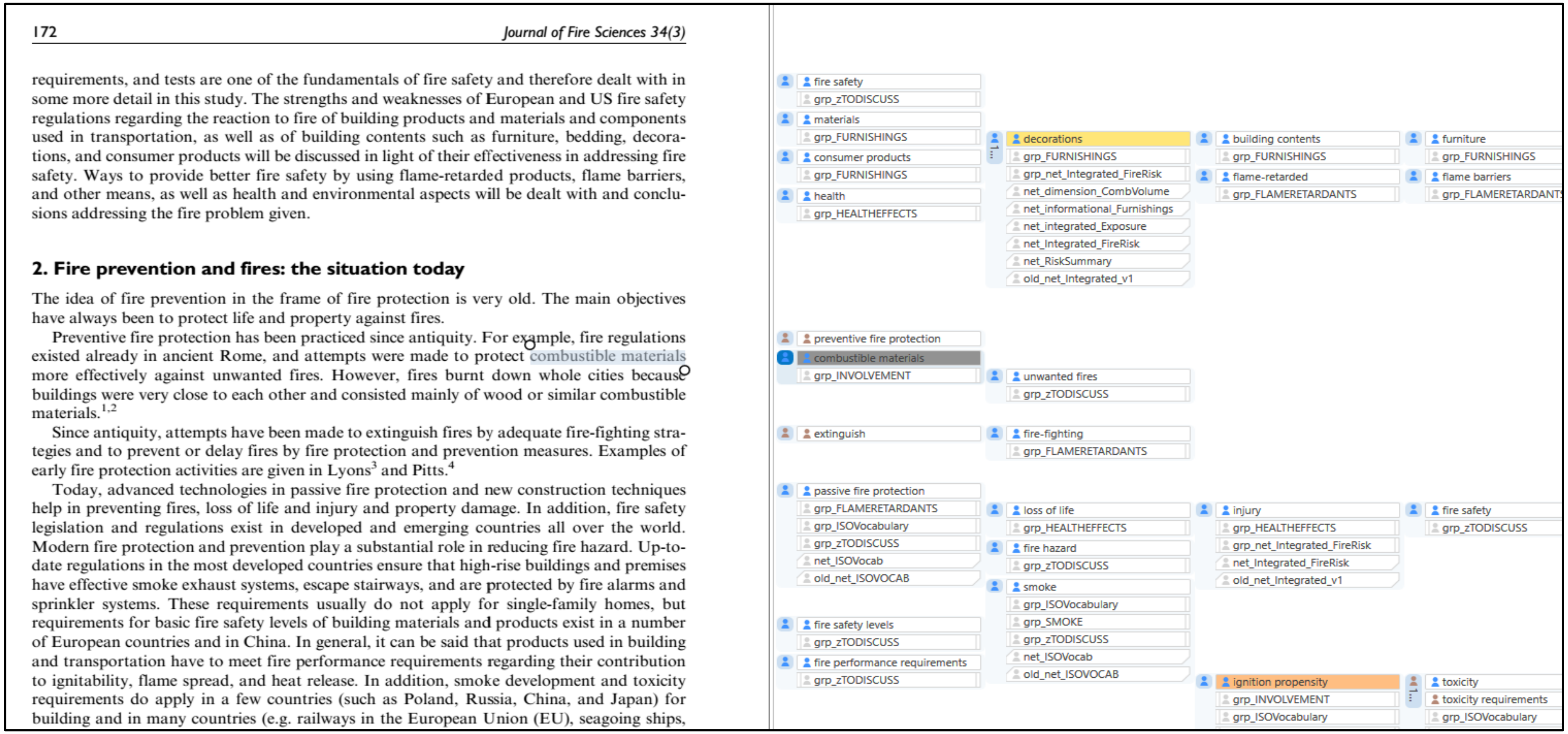


Figure 5 Segment of the overall concept network, showing how open flames are related as a potential ignition source for an item of furniture. Each term in the network is either discovered in the literature or contributed by an expert analysing the network. Here, a candle is a type of small open flame, and a small open flame is a type of open flame, and an open flame is a type of ignition source. Terms such as "candle flame ignition source" are identified as being synonymous with "candle". Larger open flames are also an ignition source, but marked in grey as outside the scope of this project, except insofar as a larger open flame (such as an open fire) might be a radiant heat source of ignition for an item of furniture. (Other colours relate to the overall model and for simplicity are explained later in this report.) This process of identifying and relating fire risk concepts is repeated for each term extracted in the annotation process, to eventually result in a formalised representation of how furniture fire risks are currently understood, directly connected to how the concepts are employed in the literature and used in discussion between experts.

Our concept modelling approach aimed to identify all terms that potentially describe an aspect of furniture fire safety that occur in our set of reviews. Terms were manually identified by being coded ("annotated" or "tagged") by a member of the research team reading a document and tagging a term as denoting a concept relating to furniture fire safety or FR exposure. This coding process was conducted in Atlas.ti version 9. Atlas.ti is computer-assisted qualitative data analysis software (CAQDAS) designed to support qualitative concept identification and analysis tasks. Tagging was conducted by one annotator, with a second annotator (PW) providing quality control checks on the annotated documents. To encourage consistency in tagging, the annotators were trained in the use of the software, provided with annotation guidelines (see Appendix 2), and regular checkpoint meetings were held to refine the annotation methodology, discuss preliminary findings and observations, suggest modifications to concept groups, and revise the annotation guidelines as needed. An excerpt of the annotation environment that shows document tags is illustrated in Figure 6.

As we were seeking to discover codes across the whole pool of literature, we conducted a “breadth-first” annotation process, whereby only the first instance of each concept was tagged. We seeded the concept modelling process by comparing the relative inverse frequency of words occurring in the literature sample with the average frequency of their occurrence on the Internet; the top 1000 terms were then manually screened for those of obvious relevance to furniture fire safety and FR exposure. These terms were then organised into thematic groups to facilitate the process of extracting and organising concepts for further analysis in developing the concept model and risk matrix.



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requirements, and tests are one of the fundamentals of fire safety and therefore dealt with in some more detail in this study. The strengths and weaknesses of European and US fire safety regulations regarding the reaction to fire of building products and materials and components used in transportation, as well as of building contents such as furniture, bedding, decorations, and consumer products will be discussed in light of their effectiveness in addressing fire safety. Ways to provide better fire safety by using flame-retarded products, flame barriers, and other means, as well as health and environmental aspects will be dealt with and conclusions addressing the fire problem given.

2. Fire prevention and fires: the situation today

The idea of fire prevention in the frame of fire protection is very old. The main objectives have always been to protect life and property against fires.

Preventive fire protection has been practiced since antiquity. For example, fire regulations existed already in ancient Rome, and attempts were made to protect combustible materials more effectively against unwanted fires. However, fires burnt down whole cities because buildings were very close to each other and consisted mainly of wood or similar combustible materials.[1,2]

Since antiquity, attempts have been made to extinguish fires by adequate fire-fighting strategies and to prevent or delay fires by fire protection and prevention measures. Examples of early fire protection activities are given in Lyons[3] and Pitts.[4]

Today, advanced technologies in passive fire protection and new construction techniques help in preventing fires, loss of life and injury and property damage. In addition, fire safety legislation and regulations exist in developed and emerging countries all over the world. Modern fire protection and prevention play a substantial role in reducing fire hazard. Up-to-date regulations in the most developed countries ensure that high-rise buildings and premises have effective smoke exhaust systems, escape stairways, and are protected by fire alarms and sprinkler systems. These requirements usually do not apply for single-family homes, but requirements for basic fire safety levels of building materials and products exist in a number of European countries and in China. In general, it can be said that products used in building and transportation have to meet fire performance requirements regarding their contribution to ignitability, flame spread, and heat release. In addition, smoke development and toxicity requirements do apply in a few countries (such as Poland, Russia, China, and Japan) for building and in many countries (e.g. railways in the European Union (EU), seagoing ships,

Figure 6 Excerpt of the annotation environment showing how a document is annotated for terms that describe furniture fire risks, for potential inclusion in the overall concept network and, ultimately, potentially quantified in the final risk matrix.

Once the annotation process was complete, each broad theme was analysed to map how the concepts were related to each other within the theme and flagging codes that may be of particular relevance to modelling fire risk in soft furnishings. The draft thematic networks were then assessed by a topic expert from the project team for validity and modified (adding, removing, and changing relationships between concepts) according to their input, to provide a model of each of the potentially significant fire risk factors that relate to the theme. This process was repeated several times for each thematic network. Once each thematic network had been finalised, they were aggregated into an overall network in which the cross-theme conceptual relationships were filled in. A flow-chart summarising the annotation process is presented on page 4 of Appendix 2; the process of mapping the relationships between concepts is illustrated in Figure 7.

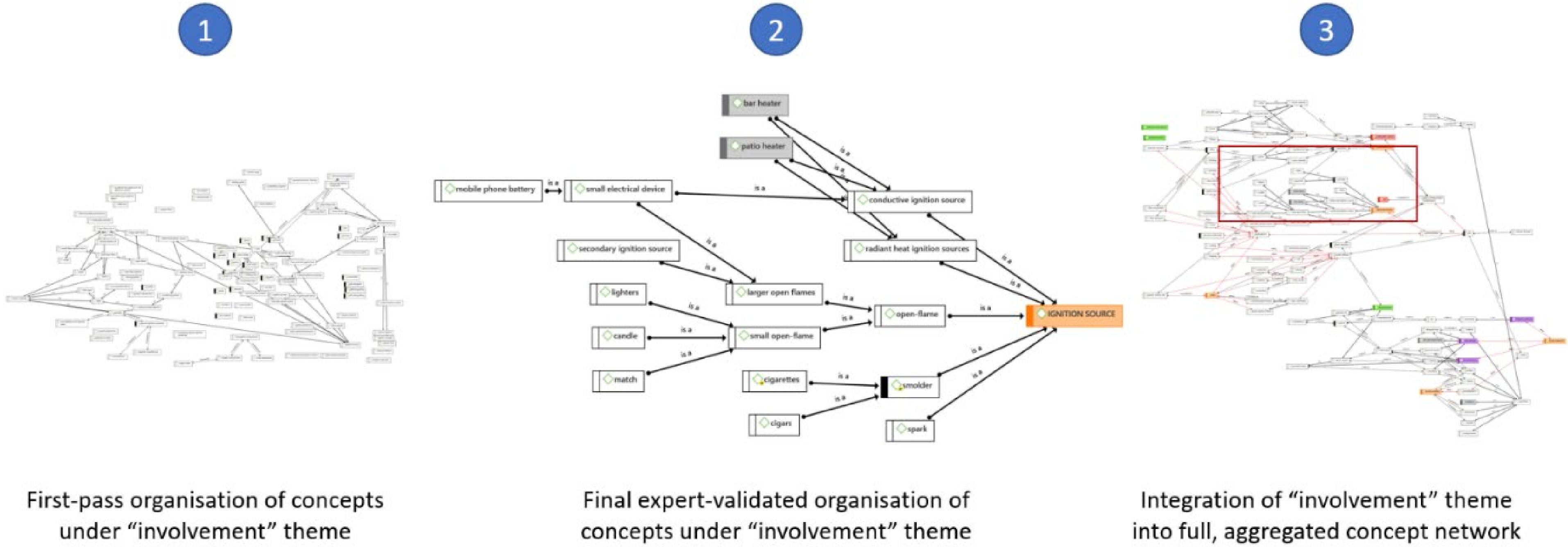


Figure 7 Illustration of the process of (1) aggregating concept codes extracted from the literature into draft networks, (2) using expert input to add missing codes, eliminate redundant or unhelpful codes, and refine the code-code relationships, before (3) integrating the theme into the overall network.

The annotation process, combined with expert contributions that included a short online workshop and an interview with two fire investigators, resulted in 2549 concept codes being considered for the concept model. The repeated process of analysing and refining the concepts and their relation to fire risk factors eventually resulted in a fire risk concept network consisting of 74 codes, and an exposure concept network of 34 codes. The networks are too large to display in this report; the fire risk matrix is shown for illustration in Figure 8 and high-resolution versions are available as digital Appendices 3 to 8.

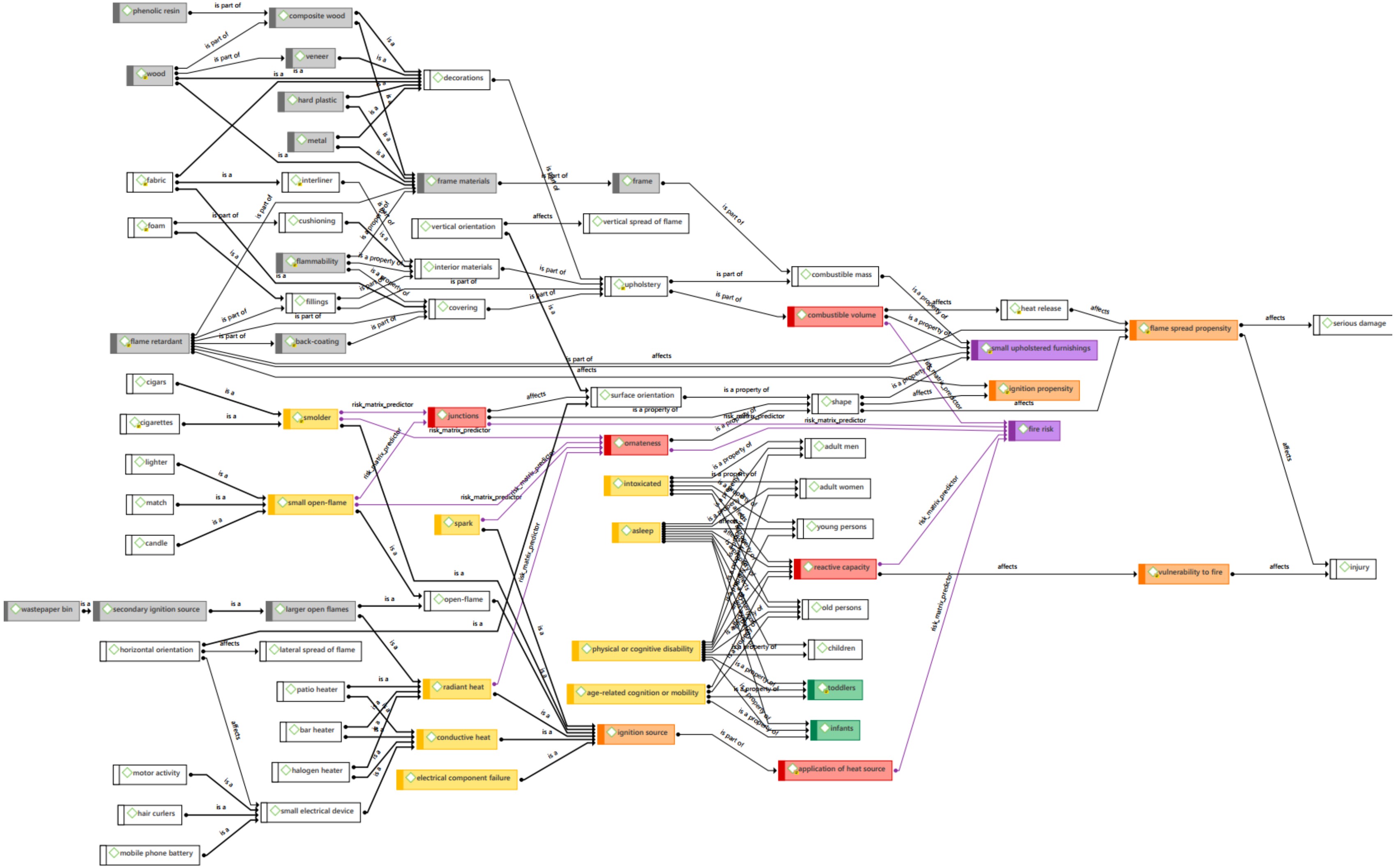


Figure 8 The complete concept model for fire risks relating to use of small items of upholstered furniture. The colour of each node corresponds to colours of each component of the risk matrix, as shown in Figure 10, to facilitate mapping the concept network onto the final risk model. Codes in grey are excluded from the model but shown to indicate how concepts that are relevant to fire risk in general, but not the specific model developed for the present task, fit in the overall concept network. A summary of inclusion decisions for network concepts in the final risk model is in Appendix 9 (code list), in the "Fire Risk Code List" sheet. A high-resolution version of the network is in Appendix 8 (fire risk and furniture integrated).

5.5 Fire risk model development

Our approach to developing the fire risk model consisted of five steps:

1. We analysed the concept network to select model dimensions and organised them into a failure model (see "Dimension selection" below);
2. We looked for empirical data that would allow us to quantify each dimension of the model (see "Identifying empirical data");
3. Since empirical data was not sufficient for reliable modelling, we developed an alternative methodology for quantifying model dimensions (see "Quantifying the matrix dimensions");
4. We collected data for the model dimensions (see "Approach to data collection);
5. We selected appropriate statistical methods for integrating the individual model dimensions into an overall risk score (see "Overall fire risk model…").

5.5.1 Dimension selection

The endpoints of concern for the modelling exercise are determined by our definition of furniture fire risk, i.e. damage to property or injury to person from fire originating in an item of small upholstered furniture.

For fire risk, the concept modelling exercise identified four key factors that contribute to overall fire risk in furniture:

- the potential for exposure to an ignition source;
- the potential for the item of furniture to ignite;
- the potential for fire to spread through the item of furniture;
- the risk of injury to a person using or near to the item from fire in the item.

These concepts are highlighted in orange in the concept network and are known to be key because they are convergence points in the concept network, with all other concepts being shown to contribute to fire risk via these nodes.

The risk concepts were then organised into a simple failure model, whereby exposure to a source of ignition may result in the ignition of an item of furniture, that may result in the spread of flame through the item of furniture, that may occur near to a person vulnerable to harm from fire in the item, that may result in injury to the person. This model is shown in Figure 9. More complex failure models can be articulated, but detailed failure models relating to the use of items of small upholstered furniture are not presented in the literature; as discussed in the next section, it is also not evident that data is available to support a higher-resolution model. To our knowledge, this is the first-time upstream use factors and downstream user vulnerabilities have been explicitly considered in modelling risk of injury or damage in relation to fire in furniture.

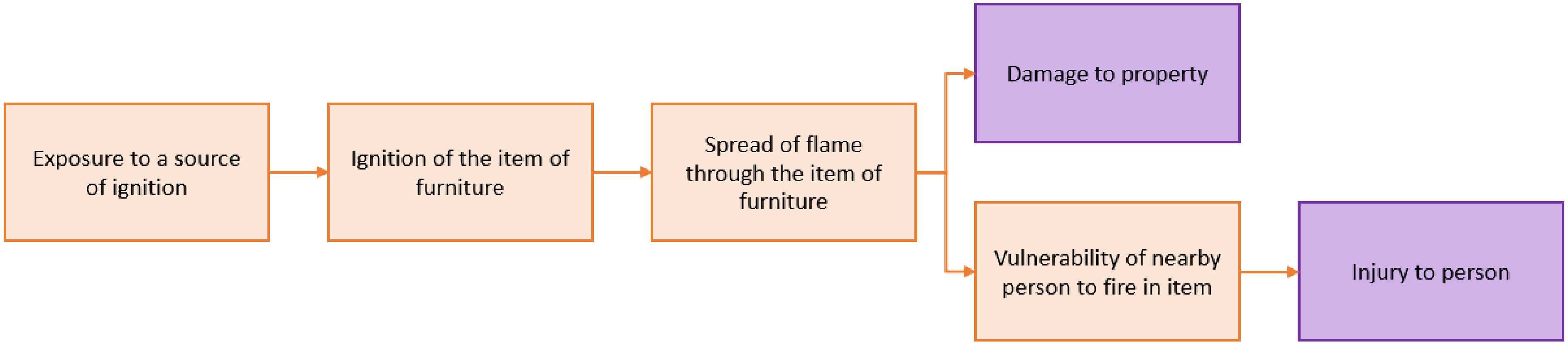


Figure 9 Failure model for risk of injury or property damage from fire occurring in small upholstered furnishings.

5.5.2 Identifying empirical data

The next step in modelling was to identify empirical evidence that could be used as input data for the model. Such data has to fulfil two conditions: that the category of data can differentiate fire risk between furniture product types; and that the data are of sufficient quantity and quality that they permit meaningful quantification of each of the model dimensions.

The need to differentiate fire risk in furniture product types excluded specific filling/fabric combinations as potential data for the model. While properties of the filling and fabric, and their combination, are critical predictors of the ignitability of a particular item of furniture, there are many potential combinations, and no currently known correlation between filling and fabric and fire behaviour of the individual furniture product[17,18]. Moreover, the fire properties of existing UK fillings and fabrics are highly dependent on the Furniture and Furnishings (Fire Safety) Regulations (FFFSRs) pertaining to them. Thus, filling and fabric flammability are furniture properties that cannot be used to differentiate risk between furniture product types.

Features from the concept modelling that we judged capable of differentiating fire risk in furniture product types included the following:

- likelihood of contact with an ignition source, as furniture use and therefore user behaviours that risk ignition would depend to some extent on furniture product type;
- the shape of an item of furniture, as this would change between furniture product types and could result in differences in places where e.g. ignition sources such as smouldering cigarettes could become lodged;
- the size of an item of furniture and therefore the amount of fuel it gives to a spreading fire; and
- the ability of a user to respond to a fire in an item, which may depend on its use (e.g. sleep products).

The principal challenge in developing the model was the lack of empirical data on the involvement of small items of upholstered furniture in fires. Fire statistics do not indicate with sufficient precision which types of furniture are involved in fires (although they do show that fires originating in a living room or bedroom, when people are more likely to be asleep, result in more fatalities); nor do they show with sufficient consistency or resolution what ignition sources directly initiate a fire in an item of furniture. As explained in Chapter 3, this is not an inadequacy of the statistics but a consequence of the unpredictable and destructive behaviour of unwanted fires. We could not therefore use these data to quantify the dimensions of our model.

To estimate the amount of empirical evidence in the published literature that relates to each of our four risk model dimensions, we conducted a comprehensive search for furniture fire safety literature in the Scopus database.[xiv] This search yielded 3885 documents. We downloaded the titles and abstracts of the documents, and created a thesaurus for the terms in our concept network. We then counted the frequency of occurrence of these terms in the titles and abstracts, to derive an estimate of how much evidence there is in relation to each

[xiv] A Scopus search for [TITLE-ABS-KEY ((furniture OR furnishing* OR upholst* OR Headboard* OR Footboard* OR "Side rail*" OR Divan* OR Cushion* OR Pillow* OR "Bean bag*" OR "Foot stool*" OR "Stretch cover*" OR Pram* OR Stroller* OR "Car seat*" OR Mattress* OR Bassinet* OR "Carry cot*" OR Playpen* OR "Play pen*" OR "Baby nest*" OR *Chair* OR "Play mat*" OR Playmat* OR "Changing mat*" OR "Pet bed*" OR "Assisted living" OR Armchair* OR Couch* OR Sofa* OR Chaise* OR Recliner* OR Chesterfield* OR Futon*) AND (flam* OR fire))] returned 3385 results (date of search: 16 August 2021). Full results are listed in Appendix 10.

concept in our concept model, and therefore for each domain in our risk model. The results of this exercise are in Appendix 9 (code list), in the worksheets "Code Thesaurus" and "Risk Term Frequency in Texts".

This exercise showed that empirical research into furniture fires most frequently focuses on fire safety tests on furniture and fabric (that we had to exclude from our model as not differentiating risk in furniture product types). Otherwise, there is very little published research into how user behaviour, furniture form factors (e.g. shape), or user vulnerability affects fire risk in upholstered furniture. The only matrix domain for which there is a relatively high quantity of literature concerns flame spread, relating to heat release from a burning item. However, because heat release depends significantly on filling and fabric combination, we could not directly use this as input data for our model.

This results in a situation whereby, although a comprehensive list of factors that affect fire safety can be aggregated and related in a concept network grounded in the literature and expert opinion, that in turn can be interpreted into a risk model, there is a lack of empirical data that can quantify how much each domain of the risk model contributes to overall fire risk when considering furniture product types. It was therefore necessary to consider other methods for quantifying the domains of the model.

5.5.3 Quantifying the fire risk domains of the risk matrix

We used the concept network to identify potential categories of data that would fulfil the following three criteria: correlates with a model domain; differentiates risk in furniture product types; and is accessible to expert judgement (e.g. it can readily be observed, or reasonably reliably known from experience). This suggested five categories of input data that could be used to quantify the model dimensions. These are presented below, and shown in Figure 35. For further information, a summary of the decision for how each code in the concept network has been handled in the model is presented in Appendix 9 in the "Fire Risk Code List" worksheet.

Likelihood of contact with an ignition source: Where and how an item of furniture is used in relation to ignition sources is a fundamental fire risk factor. It is also a behavioural factor that is critical to fire risk. Although the relative frequency by which furniture product types are exposed to ignition sources is not known, it seems reasonable to infer, for example, that an item that is generally stored in a cupboard or only used during meals would be less likely to come into contact with an ignition source than an item of furniture that is used for leisure purposes in which someone might be smoking. Likelihood of contact should therefore differentiate between furniture product types: e.g. a highchair is probably at lower risk of contact with an ignition source than an armchair. It also seems reasonable that an informed person can make a reasonably reliable judgement about whether a furniture product type is more or less likely to be exposed to an ignition source.

Number of junctions: It is known that vertical surfaces burn upwards more readily than across horizontal surfaces, as the fuel required for flame spread is in the path of the flame. Ignition that starts at the base of a vertical surface is the worst case as it has the most accessible fuel. Junctions in furniture, i.e. joins between horizontal and vertical surfaces into which e.g. a cigarette can roll and initiate a fire, tend to be where fires start and are a key component of flammability test rigs. It seems reasonable to infer that an item of furniture with more junctions should be at higher risk of ignition than an item with fewer junctions. Since, for example, a foot stool will be likely to have fewer junctions than an armchair, number of junctions should allow differentiation between furniture product types. In terms of measuring junctions, they can be counted. Since junctions present a risk only when a source of ignition is lodged in a junction, number of junctions is only included in the model if a type of furniture is judged as likely to come into contact with smokers materials.

Illustration of how junctions are counted in items of furniture. The sofa on the left has three junction points, where vertically-oriented surfaces join with horizontally-oriented surfaces. The chair on the right has only one junction point.

Ornateness of surface and shape: Ornateness was not frequently mentioned in the literature but does feature under "style factor" in a fire model cited by one of the reviews in the document set from which our concept network was derived[74]. Ornate surfaces also have more points in which an ignition source can become lodged and more catch points for ignition, with angular points providing areas which can heat up enough to potentially ignite from an open flame or other heat source. Because playmats tend to be plain objects compared to cushions, which almost always have corners and can be heavily decorated, ornateness should differentiate between furniture types. It seems reasonable that an informed person could make a judgement about relative ornateness.

Illustration of the difference between a plainer chair (left) and a more ornate sofa (right). Ornate items have complex surfaces and shapes. (Sofa image credit: theoriginalsofaco / flickr.com CC BY-NC-SA).

Combustible volume: Although heat release could not directly be used as input data for the matrix domain of fire spread, combustible volume does correlate with heat release. The total heat release of an armchair would include the heat of combustion of fabric, filling and wooden frame. However, the frame is likely to burn much more slowly than the fabric and filling, and will make a much smaller contribution to flame spread and fire growth. As discussed above, there is no obvious correlation between furniture type and foam density, so it was not appropriate to make any assumptions about contribution of foam density to burn rate. Therefore, combustible volume, not mass of fabric and filling, was selected as the best dimension to represent fire spread potential. Combustible volume should also differentiate between furniture product types, with e.g. highchairs being lower in volume than armchairs.

In terms of measuring combustible volume, the volume of upholstered material in a furniture item can reasonably be estimated from the dimensions of the item.

Reactive capacity of user or nearby person: A fire in an item of furniture only causes injuries or fatalities if, for whatever reason, a user or nearby person is not able to react and move away from the fire before they are harmed by it. As for likelihood of contact with an ignition source, this is a partly behavioural factor that greatly influences risk of injury or death from a fire, and makes the difference between a fire that causes property damage and a fire that causes personal harm. Unconsciousness through sleep or intoxication, physical or cognitive disabilities, and cognitive and physical capacities that are limited by their age (i.e. very old or very young), all potentially restrict a person's capacity to react to fire and therefore increase risk of injury or death. Different types of furniture will be more or less likely to be used by someone with restricted capacity, with e.g. armchairs and cots more likely to be used for sleeping than dining chairs or highchairs, so the reactive capacity of a user should differentiate between furniture product types. It also seems reasonable that an informed person could make a judgement about the reactive capacity of a user or nearby person.

Based on the above, we decided to use informed judgement to evaluate likelihood of contact with an ignition source, ornateness of surface and shape, and reactive capacity of a user or nearby person. Number of junctions we decided to count, and for combustible volume we estimated the volume in cubic metres of the upholstered elements of an item of furniture.

5.5.4 Approach to data collection

We captured informed judgement using a Likert scale of 1-5, on the assumption that an informed person can reasonably judge for each domain whether an item has more or less of a given property such as ornateness or risk of contact with an ignition source, but not to a level that is more granular than five points on a scale. In terms of what the Likert scores broadly mean, a score of 1 meant the evaluator considered the item to be as little ornate an item of furniture as they could conceive, be used by someone alert and mobile (or unlikely to be used by someone who is not), and as unlikely as they could conceive as to coming into contact with a source of ignition. Scores of 5 meant the opposite. Guidance notes to evaluators are shown in Column E of the questionnaires in Appendix 11.

We also captured some of the experts' reasoning, by asking for narrative text to explain the score they gave. This method gave us numbers we could analyse statistically and qualitative information about what the evaluators thought was important in coming to their judgement. The collection of written justification for scores had a number of potential uses, including assessing the comparability of judgements and their potential moderation, identifying decision factors, and mapping evaluator reasoning onto our concept network to determine if there were any risk factors that we might have overlooked.

Evaluators were presented with a questionnaire for all 33 furniture product types included within the scope of this review, plus armchairs as a control. For each type, an example item of relatively high fire risk and relatively low fire risk was shown, with the evaluators completing the questionnaire for both items. This allowed us to put a higher and lower range on evaluations of furniture product types. The questionnaire included definitions of terms and prompts for questions based on important elements of the concept network that we wanted the experts to explicitly consider. For example, this would help to ensure that specific ignition elements such as sparks and hair curlers were not accidentally overlooked. Three evaluators independently completed all the questions in each questionnaire in random order to minimise learning effects, before convening in a moderated consolidation session (moderator: PW) where they came to consensus on each score. Finally, independent evaluators were asked to complete a questionnaire for a subset of four furniture product types, to determine the extent to which the research team evaluations generalise to evaluations made by external experts. The questionnaire is shown in Appendix 11.

5.5.5 Overall fire risk model and method for calculating risk scores

The final model for fire risk in small items of upholstered furniture is shown in Figure 10. Likelihood of contact with an ignition source is scored on a scale of 1-5 and assessed by a team of three evaluators coming to a consensus view, with the evaluators providing narrative text explaining the reasoning for the judgement. The same process is applied to ornateness of surfaces and shape, and the reactive capacity of a user or nearby person. Junctions are counted. Combustible volume was calculated from the estimated volume of upholstered components of an item (calculations are shown in Appendix 12 - evaluation questionnaire with volume calculations). Two items for each furniture product type, representing a lower-risk and higher-risk example, are assessed to provide an estimated upper and lower risk range for each type of furniture.

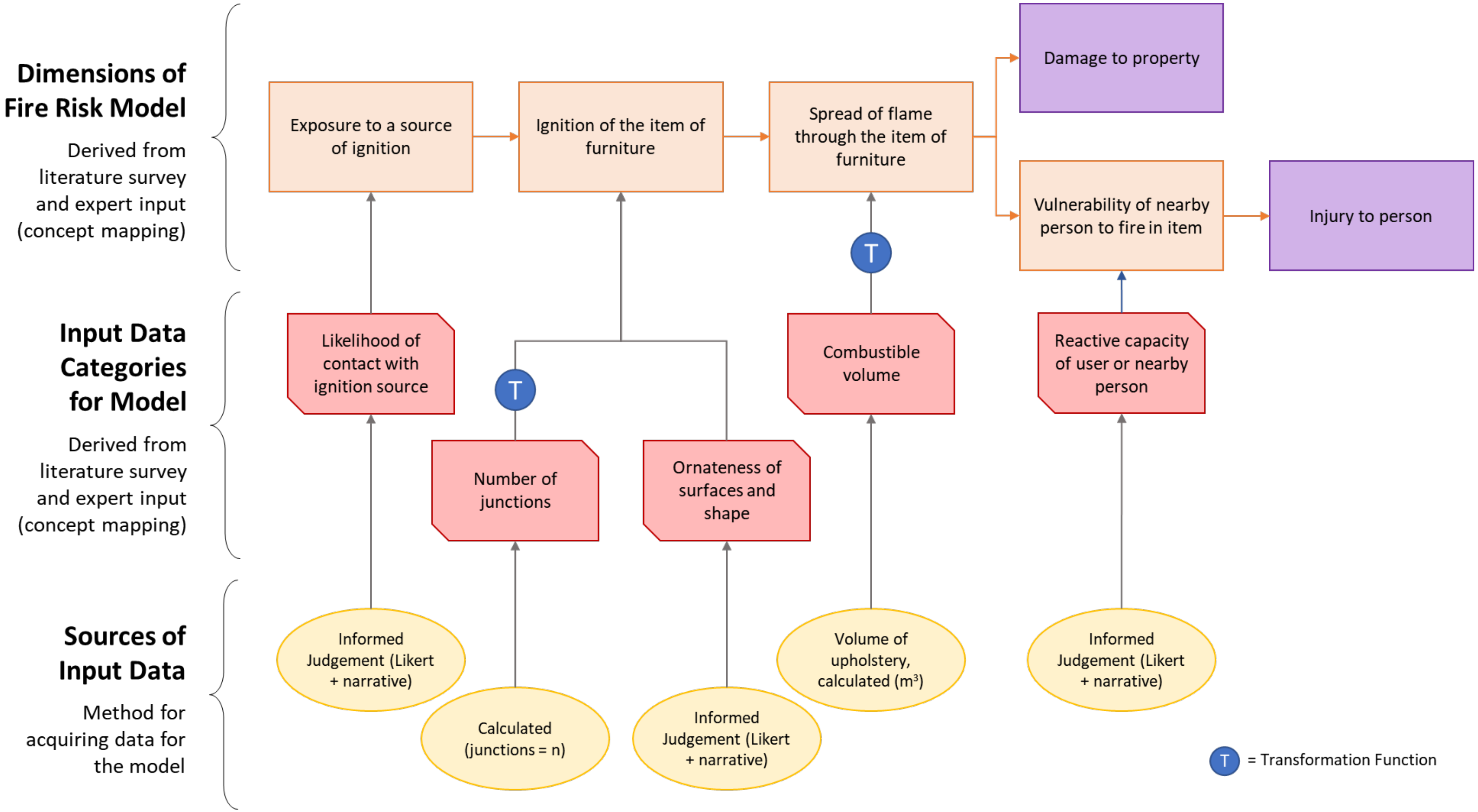


Figure 10 The overall model for fire risk in small items of upholstered furniture, showing the failure model (top row), the input data for the model (second row) and the source of input data (third row). The colours of the model match the colours of the relevant nodes in the concept network, showing how matrix dimensions are connected back to input data types, back to details in the source of the input data.

We used two transformation functions to convert the measured elements (junctions and combustible volumes) to a scale of 1-5. This was to render them combinable with the Likert scores, and reflects empirical uncertainty about how much each of these factors actually contributes to fire risk.

Junctions were transformed such that zero junctions scored 1, one scored 2, two scored 3, three scored 4, and four or more scored 5. This was on the rationale that an object with four junctions could effectively be an open box (such as a basket or bassinet), from which an ignition source would not be able to roll anywhere except into a junction, and therefore represented maximum risk on that domain. Objects with 5 or more junctions were considered complex objects and conservatively assumed to present equal risk to an open box. Finally, because junctions only present a risk in relation to ignition sources that can fall into a join point in an item of furniture, the junction score was only included in the overall risk score if the evaluators referred to candles or smokers materials in the narrative justification for scoring ignition source. (Narrative justifications are shown in the “Furniture Justifications” sheet of Appendix 15 furniture matrix data analysis.)

Combustible volume was assumed to have linear increase in risk up to a maximum score of 5 for a volume of 0.009 m^3. 0.009 m^3 is the volume of a small cushion, a threshold above which we assumed flame spread is effectively guaranteed. The transformation functions are shown in the “Risk Tables” sheet of Appendix 15 furniture matrix data analysis.

In terms of calculating overall risk scores, we considered three models: a first-quartile; a mean average, and a low-score “clamp point” model. How each of these would provide a different fire risk score for a given set of domain evaluation scores is shown in Table 16.

The clamp-point model scores according to the lowest score, and is a fair approximation of true risk in a failure model because it treats risk as a function of failure at the weakest point in the system. For example, an item can be very likely to be exposed to a source of ignition, have high combustible volume, and be very likely to be used by someone with limited capacity to react; however, if the item is very unlikely to ignite, then the other three risk factors being high could be viewed as irrelevant to risk - hence, the low score for likelihood of ignition becomes the clamp point for the overall risk score.

Table 16: Illustration of potential fire risk model outputs for different methods of score calculation.

Model	Domain Scores	Risk Score
Low-score “clamp point”	1, 2, 5, 5	1.00
Mean	1, 2, 5, 5	3.25
Lower quartile	1, 2, 5, 5	1.75

We rejected the clamp-point model because, although with robust data in a well-defined failure model it could arguably model risk quite accurately, when data is uncertain the increased likelihood of an error in a low value when judged by informed evaluators increases the likelihood of the final score underestimating fire risk. The low-point model also relies on the “saving mechanism” working every time; thus, a model that is not determined by a single low score leaves some space for hard-to-predict unlucky circumstances and unforeseen use cases, and would be more conservative in predicting fire risk.

We rejected the mean average model as it gives too much weight to the higher and lower values, thus does not map well to the general concept of the failure model that underpins our fire risk model.

Our preferred model was the lower quartile, as this puts more weight on the lower values but is not fully determined by the lowest value, giving a somewhat clamped estimate of fire risk that better reflects potential for error given the way data is gathered for the model, and desirable conservativism in predicting fire risk. We present the results of all three models in the “Fire Model Scores” sheet of Appendix 15 (furniture matrix data analysis) to show the range of uncertainty introduced by the assumptions in our model decision.

Because there are two termini (injury and property damage) to our risk model, we calculated two model outputs, showing injury risk as a function of all four domains as our primary output, and damage risk as a function of all domains except reactive capacity as a secondary output.[xv] Since the judgements from which the scores are derived are based on perceived relative importance, rather than being grounded in empirical evidence of absolute risk, the models show relative risk of injury or damage between furniture product types.

5.6 Fire retardant exposure model development

Our approach to developing the fire retardant exposure model was similar to that of the fire risk model:

1. We analysed the exposure concept model (shown in Figure 11, with a high-resolution version in Appendix 7 concept network exposure) to select a set of dimensions that would model human exposure to fire retardants from furniture while in use;
2. We determined whether there are sufficient empirical data to quantify each dimension of the model;
3. Since empirical data were not sufficient for reliable modelling, we developed an alternative methodology for quantifying model dimensions;
4. We collected data for the model dimensions;
5. We selected appropriate statistical methods for integrating the individual model dimensions into an overall exposure score.

[xv] Note that we show in Figure 16 that injury and property damage are closely correlated, and we therefore exclusively present the injury outcome of the matrix as our results.

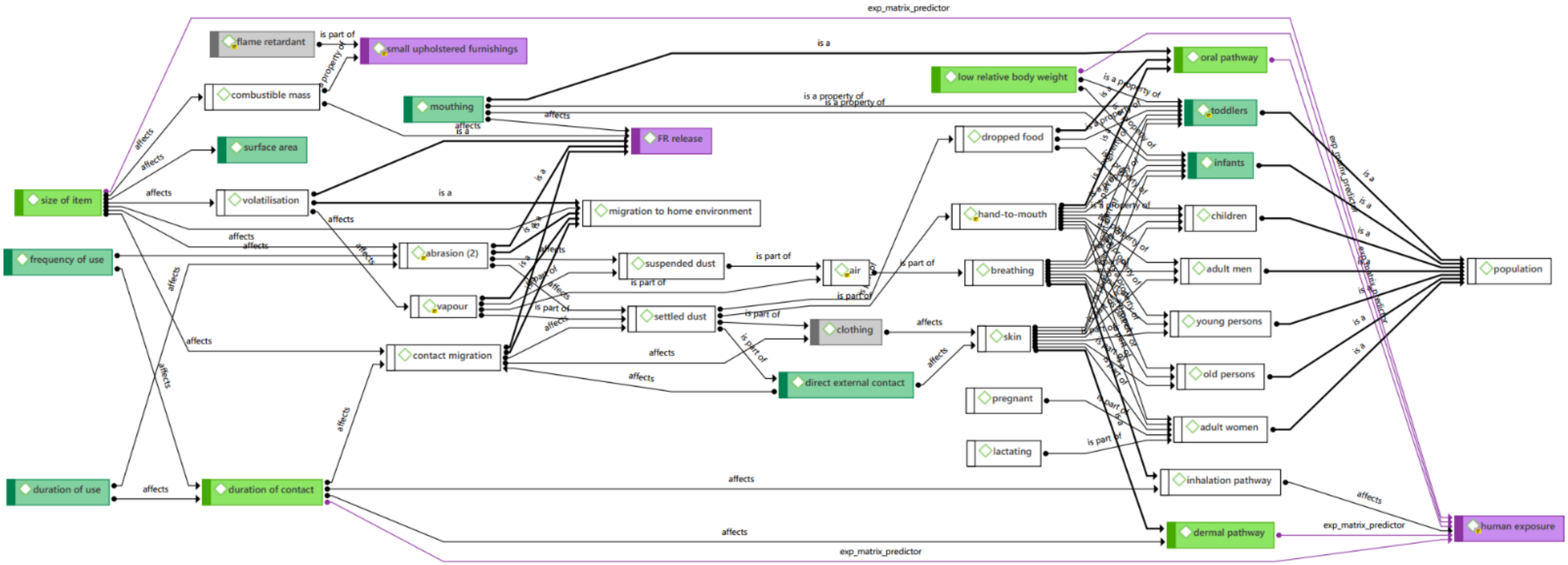


Figure 11: The complete concept model for exposure to fire retardants resulting from the use of small items of upholstered furniture in the domestic environment. The colour of each node corresponds to colours of each component of the model, as shown in Figure 13, to facilitate mapping the concept model onto the exposure model. Codes in grey are excluded from the model but shown to indicate how concepts that are relevant to exposure in general, but not the specific model developed for the present task, fit in the overall concept network. A summary of inclusion decisions for network concepts in the final risk model is in Appendix 9, in the "Exposure Code List" sheet. A high-resolution version of the network is shown in Appendix 7.

5.6.1 Dimension selection

For exposure, the concept modelling exercise identified five key concepts that determine overall exposure to CFRs from the use of furniture: a low body weight of the user (i.e. a very young user of an item whose low body weight means that a unit exposure to CFRs exceeds that of an adult when normalised to body weight); dermal migration of CFRs from an item (i.e. via direct skin contact with the item); oral migration of CFRs from an item (i.e. mouthing of an item); duration of contact with an item (i.e. cumulative time of use); and size of an item of furniture (representing the CFR load an item can contribute to the domestic environment, resulting in indirect exposure to CFRs from furniture through breathing CFR-containing air and ingesting or breathing CFR-contaminated dust).

We did not identify an obvious chain of events leading to exposure that would be relevant for modelling purposes, at least in relation to the defined task. Rather, there are general pathways of release from furniture and migration to an individual that are approximately cumulative in terms of determining exposure from a furniture product type. Four exposure factors contribute to direct personal exposure (low body weight; dermal migration; oral migration; duration of contact), Figure 12. One exposure factor (size of furnishing item) covers indirect exposure via release of FRs to the home environment.

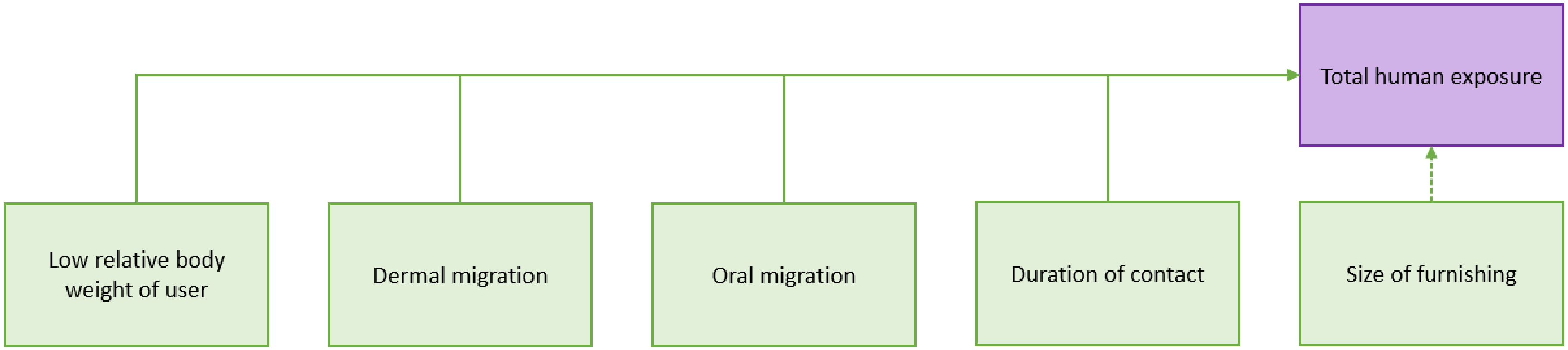


Figure 12 Model for potential exposure to fire retardants from use of small upholstered furnishings. Solid lines represent direct indicators of increased exposure; dotted lines represent indirect indicators.

5.6.2 Identifying empirical data

Similar to the fire risk model, to be suitable for use in the exposure model, empirical evidence has to fulfil two conditions: (a) that the category of data can differentiate exposure potential between furniture product types; and (b) that the data are of sufficient quantity and quality to permit meaningful quantification of each of the model dimensions.

It was not feasible to conduct the same keyword analysis of the literature as we did for fire risk to evaluate the potential availability of empirical data relating to exposure, as the literature was too extensive to be searched, screened, and analysed within the timeframe of the project. We do, however, know that none of the reviews discussed in detail how specific items of furniture contribute to a person’s exposure to FRs. We also know that exposure studies are not able to differentiate exposure sources to that degree of granularity. While it is possible, for example, to measure how much people are exposed to FRs in the immediate domestic environment, no data have been published showing how much FR load is specifically from furniture, and certainly not from individual furniture product types. This is explained in more detail in Appendix 16.

Similar to characterising fire risk, this left us in a situation whereby, although we have a comprehensive list of factors that could affect FR exposure from furniture, there is a lack of empirical data that can quantify how much each risk dimension contributes to overall exposure risk when considering furniture product types.

5.6.3 Quantifying the FR exposure domains

We used the concept network to identify potential categories of data that would fulfil the following three criteria: correlates with a model dimension; differentiates FR exposure in furniture product types; and is accessible to informed judgement (e.g. it can readily be observed, or reasonably reliably known from experience). This suggested five categories of input data that could be used to quantify the model dimensions. These are presented below. For further information, a summary of the decision for how each code in the concept network has been handled in the model is presented in Appendix 9 in the “Exposure Code List” worksheet.

Likelihood by use of young child: Infants and toddlers tend to be more exposed to fire retardants because they ingest more dust, breathe more air, and consume more food relative to their body weight than an adult. Some furniture is specifically designed for infants and toddlers to use; therefore, potential for exposure according to likelihood of use by a young child should differentiate between furniture product types. It seems reasonable that an informed evaluator can make a reasonably reliable judgement about when an item of furniture is likely to be used by an infant or toddler.

Likelihood of contact with bare skin: Dermal migration, alongside oral ingestion and inhalation, is one of three broad exposure routes to CFRs in furniture. Clothing acts as a barrier to dermal migration but bare skin will absorb fire retardants; therefore, the more bare skin in contact with an item of furniture, the greater the FR exposure. Some types of furniture are more likely to be used relatively undressed or be in contact with bare skin than others (pillows will contact bare heads, whereas, for example, dining chairs will be less likely to be in contact with bare skin); skin contact should therefore differentiate between some furniture product types. It also seems reasonable that an evaluator could judge the amount of bare skin likely to be in direct contact with an item of furniture.

Likelihood of mouthing an item: Oral migration is another of the three broad exposure routes to fire retardants. This occurs through ingestion of house dust, from hand-to-mouth behaviours, and through direct mouthing of furniture. While hand-to-mouth behaviours and dust are indirect sources of exposure to FRs, and are covered under the dimension of migration to the home environment, mouthing behaviours are a direct route of exposure to

FRs in furniture. Since mouthing behaviours are specific to very young children, and some furniture is designed for young children, it should be possible to differentiate furniture product types on this dimension. It should also be possible for an informed evaluator to judge the relative likelihood of mouthing behaviours for a given item of furniture.

Cumulative use of an item: The longer someone is in contact with an item (the more frequently and the longer for which they use it), the greater the exposure to FRs whatever the route. More heavily-used items can also be expected to release more FRs through abrasion and, if warmed by body temperature, potentially also through volatilisation. Some furniture product types are also designed to be used for longer periods of time than others (e.g. beds or armchairs vs. highchairs or stools); duration of contact should therefore differentiate between furniture product types. It should also be possible for an informed evaluator to judge the relative duration of contact with an item of furniture.

Surface area of an item: General migration of FRs from an item of furniture to the home environment occurs through abrasion of the item (physical wear releasing FRs associated with, for example, fabric fibres); contact migration (e.g. dust landing on an item of furniture, and FRs partitioning from furniture to the dust); and volatilisation, whereby FRs evaporate from the furniture to surrounding air. These result in the general presence of FRs in the home environment, to which people are exposed via inhalation, hand-to-mouth behaviours, and ingestion of dust. Larger items are a larger potential reserve of FRs and can therefore be expected to release more fire retardants; since surface area correlates with size, and likely correlates better with FR release than volume alone, it makes sense to measure surface area. Since some types of furniture differ in size (e.g. adult beds are larger than child beds, and armchairs are larger than cushions), surface area should differentiate between furniture product types. The surface area of an item can be calculated from information about the product dimensions.

Based on the above, we decided to use informed judgement to evaluate likelihood of use of an item by a young child, likelihood of contact with bare skin, likelihood of mouthing, and cumulative use of an item. Surface area was estimated in square metres, based on the shape and reported dimensions of an item of furniture.

5.6.4 Approach to data collection

We decided to capture informed judgement for use by a young child, bare skin, mouthing, and cumulative use on a Likert scale of 1-5, on the assumption that a person can reasonably judge higher vs. lower for each of these input data categories, but not to a level that is more granular than five steps on a scale. We also decided to capture some of the experts' reasoning by asking for narrative text to explain the score they gave. As for fire risk dimensions, this method gave us numbers we could analyse statistically and qualitative information about what the evaluators thought was important in coming to their judgement.

Evaluators were presented with a questionnaire for all 33 furniture product types included within the scope of this review, plus armchairs as a control. For each type, an example item of relatively high fire risk and relatively low fire risk was shown, with the evaluators completing the questionnaire for each item. The same examples were used for the exposure questionnaire as for the fire risk questionnaire. This allowed us to put a higher and lower range on evaluations of furniture product types. The questionnaire included definitions of terms and prompts for questions based on important elements of the concept network that we wanted the experts to explicitly consider. Two evaluators (SH and PW) independently completed all the questions in each questionnaire in random order to minimise learning effects, before convening in a consolidation session where they came to consensus on each score. The questionnaire is shown in Appendix 13.

5.6.5 Overall exposure model and method for calculating exposure scores

The final model for FR exposure potential in small items of upholstered furniture is shown in Figure 13. Likelihood of use by a young child of an item of furniture is scored on a scale of 1-5 and assessed by a pair of informed evaluators coming to a consensus view, with narrative text explaining the reason for the judgement. The same process is followed for likelihood of contact with bare skin, mouthing, and the cumulative use of an item. Surface area was estimated by treating items as joined oblongs or cylinders, depending on shape (calculations are shown in the raw data file Appendix 14 - evaluation questionnaire with surface area). Two items for each type, representing a lower-risk and higher-risk example, are assessed to provide an estimated upper and lower risk range for each type of furniture.

We used a log transformation function to convert surface area to a scale of 1-5. This was to render the measure combinable with the Likert scores, reflect empirical uncertainty about how much each of these factors actually contributes to FR exposure, and enable small changes in surface area for small objects to be as important as large changes in surface area for large objects. The transformation function is shown in the “Risk Tables” sheet of Appendix 15. There is a risk this may overestimate exposure from small items; to allow reproducibility and third-party testing of our assumptions, the log transform is provided in the Risk Tables sheet of Appendix 15.

In terms of calculating overall exposure score, we used the arithmetic mean. This reflected general uncertainty about the relative importance of one domain over another, resulting in an overall lack of rationale for weighting one domain more heavily than any other. Because the judgements from which the scores are derived are based on perceived relative importance, rather than being grounded in empirical evidence of absolute exposure to FRs, the model shows relative potential for exposure between furniture product types.

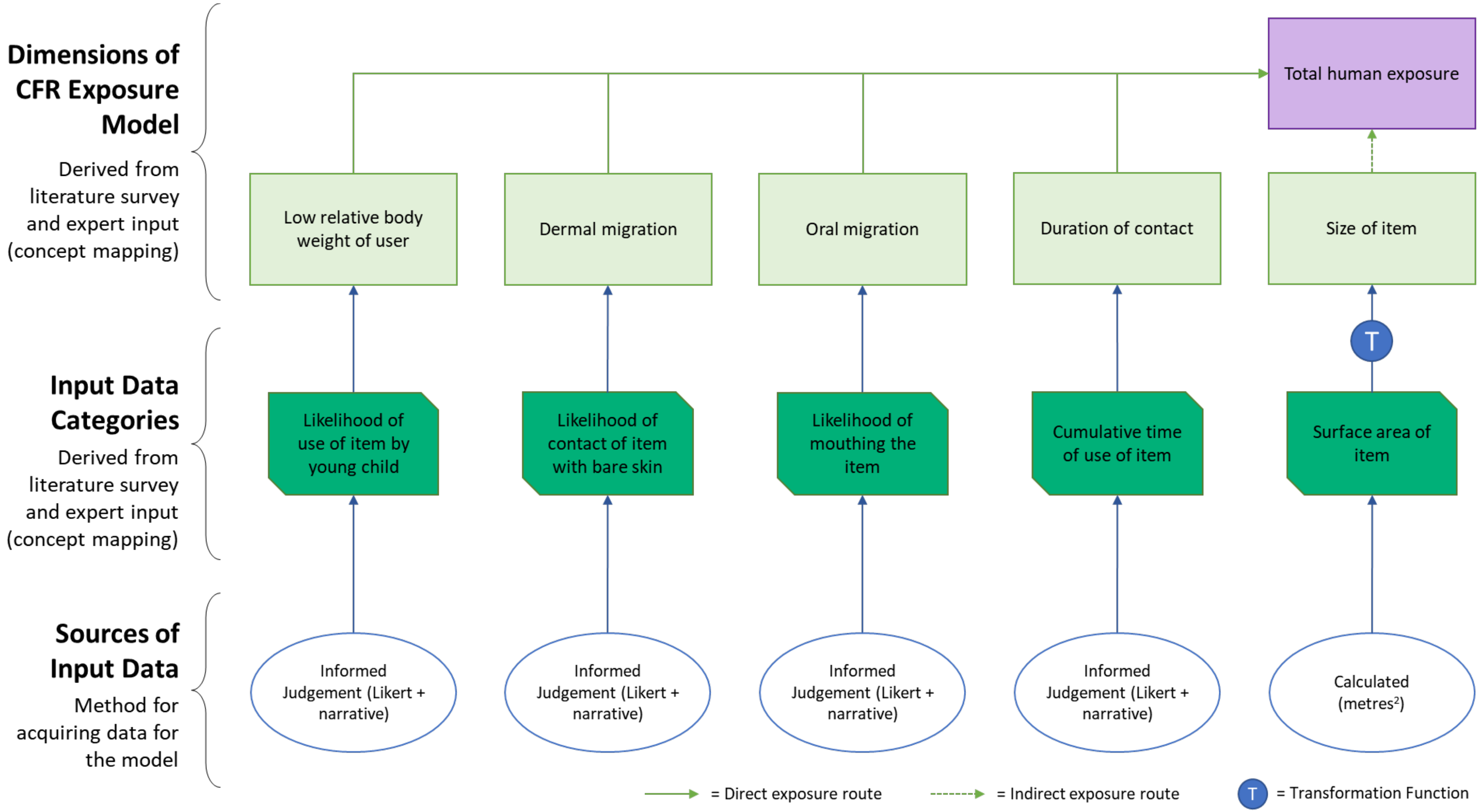


Figure 13 The overall model for potential exposure to FRs from the use of small items of upholstered furniture, showing the exposure model (top row), the input data for the model (second row) and the source of input data (third row). The colours of the model match the colours of the relevant nodes in the concept network, showing how matrix dimensions are connected back to input data types, back to details in the source of the input data.

6. The furniture fire safety matrix

6.1 Matrix of fire risk against fire retardant exposure

In Figure 14, we use a scatter chart to plot relative risk of injury in fire against potential for exposure to fire retardants for each furniture product type in the scope of our review. The chart also includes armchairs, which were used as a reference point. The plotted score is the 25th percentile of the matrix dimension scores. The ellipses represent the scores for the high and low risk variants of the furniture product types, with the point plots being the average of the high and low scores. The values for the plot are shown in Table 17.

In the scatter plot, furniture product types that tend toward the upper left of the distribution show higher relative exposure potential and lower injury risk; types that tend toward the bottom right of the distribution show lower relative potential for exposure and higher injury risk. Because injury risk and fire damage correlate closely (Figure 16) we present the matrix in terms of exposure potential vs. injury risk exclusively.

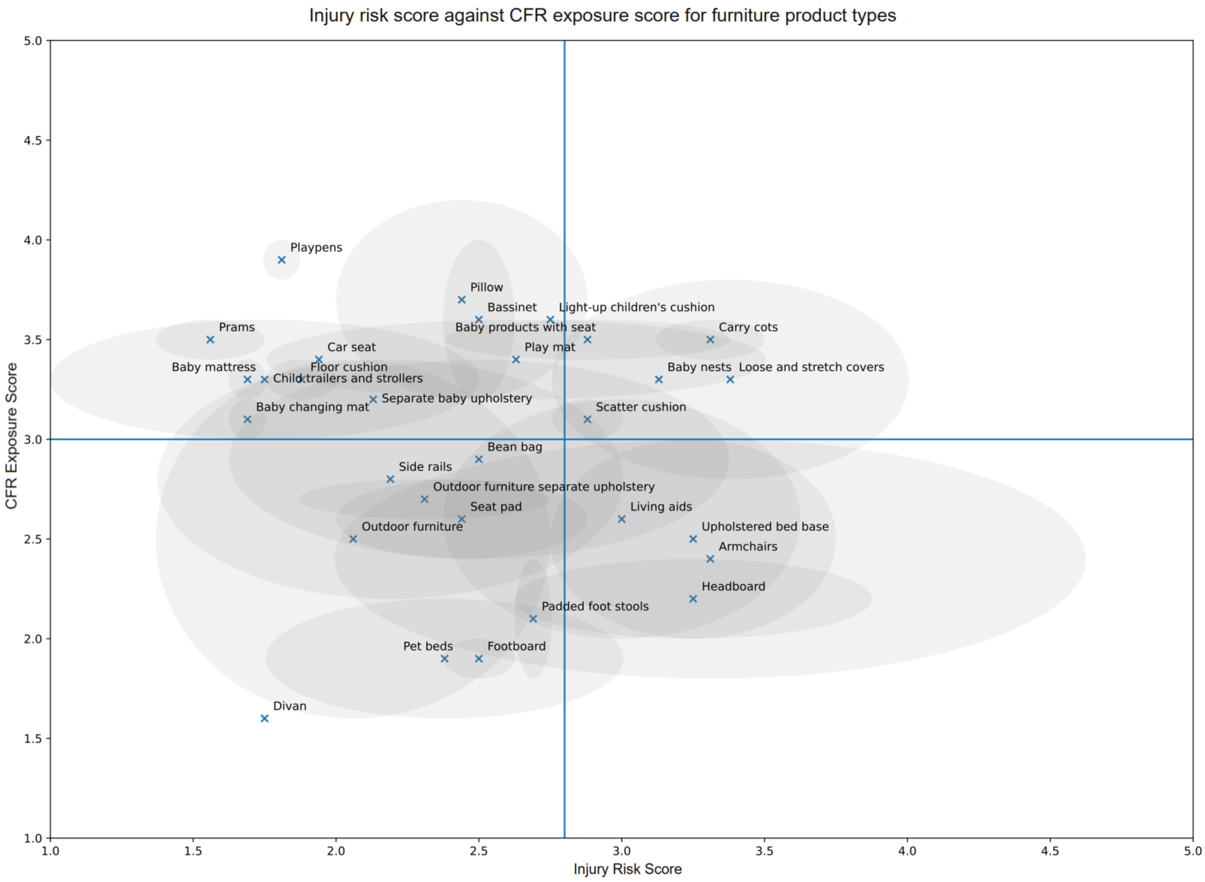


Figure 14 Risk matrix plotting relative risk of injury of user from fire occurring in a type of furniture against relative potential for fire retardant exposure from that type of furniture. Points represent the risk score of an item, the shaded area the score for the lower-risk vs. higher-risk variants of the type. A high-resolution version of this plot is shown in Appendix 18.

To follow up on the suggestion in the scatter plot of systematic differences between furniture product types, especially baby furniture against other types, we reanalysed the data using a dendrogram. Here, injury risk, damage risk, and exposure potential scores were generated for all furniture product types, and a matrix calculated to show the distances in Euclidean space between each furniture product type. We then visualised this distance using the dendrogram shown in Figure 15. The top of each u-shaped link between furniture product types shows the distance between items, or between clusters of items, with taller cross bars indicating larger differences.

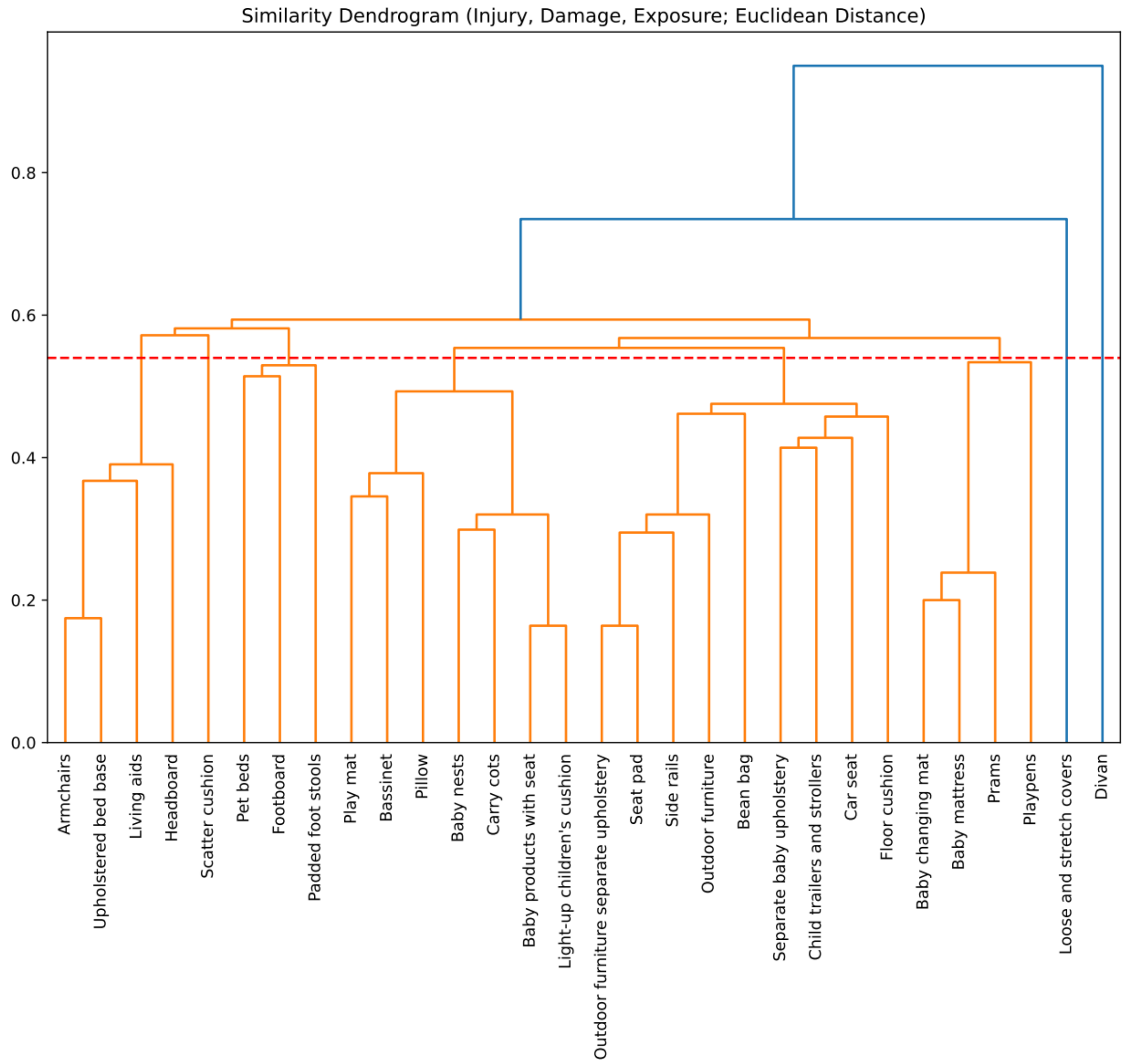
By examining the links that cross a given horizontal point on the dendrogram (indicated by the red line), we can identify a set of clusters in the data. The clusters group furniture product types according to an aggregated risk and exposure profile. While this is an interpretive task, we believe there is evidence for five clusters and three unclustered outliers, suggesting the following groupings:

- **Baby products**: Clusters 1 and 3 consist almost exclusively of baby and small child products. Cluster 2 consists of a mix of baby and small child products, that also includes bean bags, outdoor furniture, and floor cushions. While we would be hesitant to assert that any non-baby products are equivalent in risk profile to baby products, as few product types were assessed, it does suggest that some baby products have similar fire risk and exposure profiles, as was suggested by the scatter plot.

- **Larger upholstered products**: Cluster 5 consists of large bed bases (those including a headboard and footboard) seem to share a risk profile with armchairs, which might be expected as both are potentially slept in and smoked in.

- **Unclustered outliers**: Loose covers were a particularly significant outlier, probably because they were evaluated as being used on an item of furniture, therefore adopting the properties of the furniture product type they were on (the high risk cover was for a large sofa, a furniture product type that was otherwise outside the scope of this project). A relatively large number of groups containing only one type might be due to significant differences between furniture product types, or the relatively small number of furniture product types other than baby products being included in this research.

We emphasise that the positioning of the horizontal line on the dendrogram is a subjective decision; however, groups created by the positioning of the line should be explainable and non-arbitrary. Moving the line to 0.5 on the Y-axis would reduce the number of clusters: clusters 3 and 5 would be unchanged; cluster 2 would be split into play mat, bassinet and pillow, and baby nest, carry cot, baby product with seat, and light-up cushion; playpens would be removed from cluster 1 and become an outlier. The practical effect on overall groupings is relatively marginal, supporting the robustness of the model for differentiating most baby and small child furniture types from most other types.



Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Outliers
Playpens	Floor cushions	**Light-up children's cushion**	Padded foot stools	Headboards	Divans
Prams	**Car seats**	**Baby products with seat**	Footboards	Living aids	Loose and stretch covers
Baby mattresses	**Child strollers and trailers**	**Carry cots**	Pet beds	Upholstered bed bases	Scatter cushions
Baby changing mats	**Baby separate upholstery**	**Baby nests**		Armchairs	
	Bean bags	Pillows			
	Outdoor furniture	**Bassinets**			
	Side rails	**Play mats**			
	Seat pads				
	Outdoor furniture separate upholstery				

Figure 15: Similarity dendrogram indicating 5 clusters of furniture product types. Child and infant products are shown in bold. A high-resolution version of the dendrogram is shown in Appendix 17.

Table 17. Fire risk and exposure potential scores for furniture product types

	Risk of Injury Score		CFR Exposure Potential	
Furniture Type	**low**	**high**	**low**	**high**
Armchairs	2.00	4.63	1.80	3.00
Baby changing mat	1.63	1.75	3.00	3.20
Baby mattress	1.63	1.75	3.20	3.40
Baby nests	3.13	3.13	3.20	3.40
Baby products with seat	2.38	3.38	3.40	3.60
Bassinet	2.38	2.63	3.20	4.00
Bean bag	1.63	3.38	2.40	3.40
Car seat	1.88	2.00	3.40	3.40
Carry cots	3.13	3.50	3.40	3.60
Child trailers and strollers	1.00	2.50	3.00	3.60
Divan	1.75	1.75	1.60	1.60
Floor cushion	2.00	1.75	3.40	3.20
Footboard	2.38	2.63	1.80	2.00
Headboard	2.63	3.88	2.00	2.40
Light-up children's cushion	2.75	2.75	3.60	3.60
Living aids	2.38	3.63	2.00	3.20
Loose and stretch covers	2.75	4.00	2.80	3.80
Outdoor furniture	1.38	2.75	1.60	3.40
Outdoor furniture separate upholstery	1.88	2.75	2.60	2.80
Padded foot stools	2.63	2.75	1.80	2.40
Pet beds	1.75	3.00	1.60	2.20
Pillow	2.00	2.88	4.20	3.20
Play mat	1.75	3.50	3.20	3.60
Playpens	1.88	1.75	3.80	4.00
Prams	1.38	1.75	3.40	3.60
Scatter cushion	2.75	3.00	3.00	3.20
Seat pad	2.00	2.88	2.40	2.80
Separate baby upholstery	2.50	1.75	3.20	3.20
Side rails	1.38	3.00	3.40	2.20
Upholstered bed base	2.75	3.75	2.00	3.00

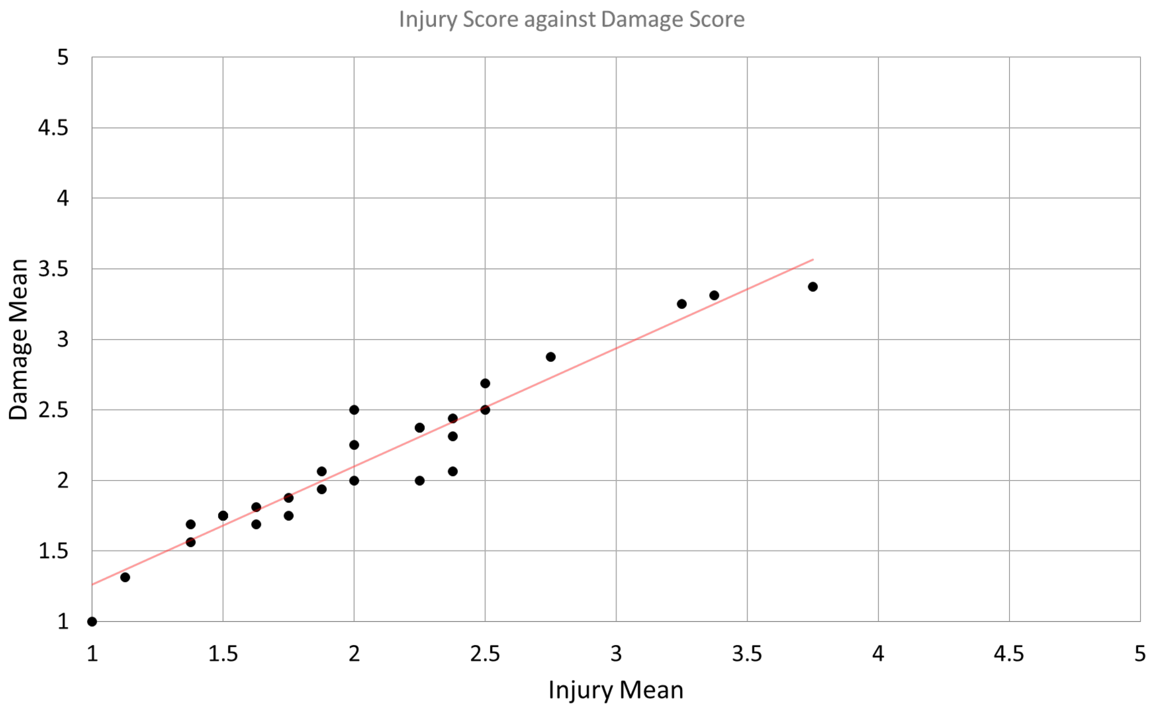


Figure 16 Plot of scores from fire risk model with damage outcome against scores of risk model with injury outcome.

6.2 Scores for individual furniture product types

6.2.1 Fire risk scores

In Table 18 we show the input data, domain scores, and fire risk score for the fire risk dimension of the matrix. The data for all 30 furniture product types are shown in the "Fire Model Scores" sheet of Appendix 15.

As described above, the ignition score is a function of a judgement of ornateness (score of 1-5 on a Likert scale), number of junctions (counted and converted to a scale of 1-5), and possibility of contact with smokers' materials (activating the junction count to contribute to fire risk score). The remaining scores are judgements on a Likert scale of 1-5. The risk score is the first quartile of the combined scores.

Table 18 Input data and domain scores for fire risk dimension of the furniture matrix.

Input data to the model

Ref No.	Furniture Type	Risk Variant	Contact with Ignition Source	Contact Reasoning	Number of Junctions	Ornateness	Combustible Volume	Reactivity of Person
25	Baby changing mat	high	2	*Narrative text*	3	2	0.04	2
25	Baby changing mat	low	2	*Narrative text*	0	1	0.02	2
26	Pet beds	high	4	*Narrative text*	3	2	0.15	3
26	Pet beds	low	3	*Narrative text*	0	1	0.00	2
27	Outdoor furniture	high	2	*Narrative text*	4	3	0.70	3
27	Outdoor furniture	low	2	*Narrative text*	0	2	0.02	1
28	Outdoor furniture separate upholstery	high	3	*Narrative text*	0	3	0.02	3
28	Outdoor furniture separate upholstery	low	3	*Narrative text*	0	2	0.01	2
29	Living aids	high	4	*Narrative text*	2	2	0.44	5
29	Living aids	low	3	*Narrative text*	3	1	0.01	2
30	Armchairs	high	5	*Narrative text*	3	3	0.24	5
30	Armchairs	low	3	*Narrative text*	1	2	0.04	2

First transformations: contact reasoning, junctions and volume converted to true/fals and scores

Ref No.	Furniture Type	Risk Variant	Smoking or Candle Ignition Source	Junction Score	Ornateness	Flame Spread
25	Baby changing mat	high	FALSE	0	2	3
25	Baby changing mat	low	FALSE	0	1	2
26	Pet beds	high	TRUE	4	2	5
26	Pet beds	low	TRUE	1	1	1
27	Outdoor furniture	high	TRUE	5	3	5
27	Outdoor furniture	low	TRUE	1	2	2
28	Outdoor furniture separate upholstery	high	TRUE	1	3	2
28	Outdoor furniture separate upholstery	low	TRUE	1	2	1
29	Living aids	high	TRUE	3	2	5
29	Living aids	low	TRUE	4	1	1
30	Armchairs	high	TRUE	4	3	5
30	Armchairs	low	TRUE	2	2	3

Second transformation: domain scores integrated to create fire risk score

Ref No.	Furniture Type	Risk Variant	Exposure to Ignition Source	Ignition of Item	Flame Spread	Vulnerability	Integrated Fire Risk Score
25	Baby changing mat	high	2	1	3	2	1.75
25	Baby changing mat	low	2	0.5	2	2	1.63
26	Pet beds	high	4	3	5	3	3.00
26	Pet beds	low	3	1	1	2	1.00
27	Outdoor furniture	high	2	4	5	3	2.75
27	Outdoor furniture	low	2	1.5	2	1	1.38
28	Outdoor furniture separate upholstery	high	3	2	2	3	2.00
28	Outdoor furniture separate upholstery	low	3	1.5	1	2	1.38
29	Living aids	high	4	2.5	5	5	3.63
29	Living aids	low	3	2.5	1	2	1.75
30	Armchairs	high	5	3.5	5	5	4.63
30	Armchairs	low	3	2	3	2	2.00

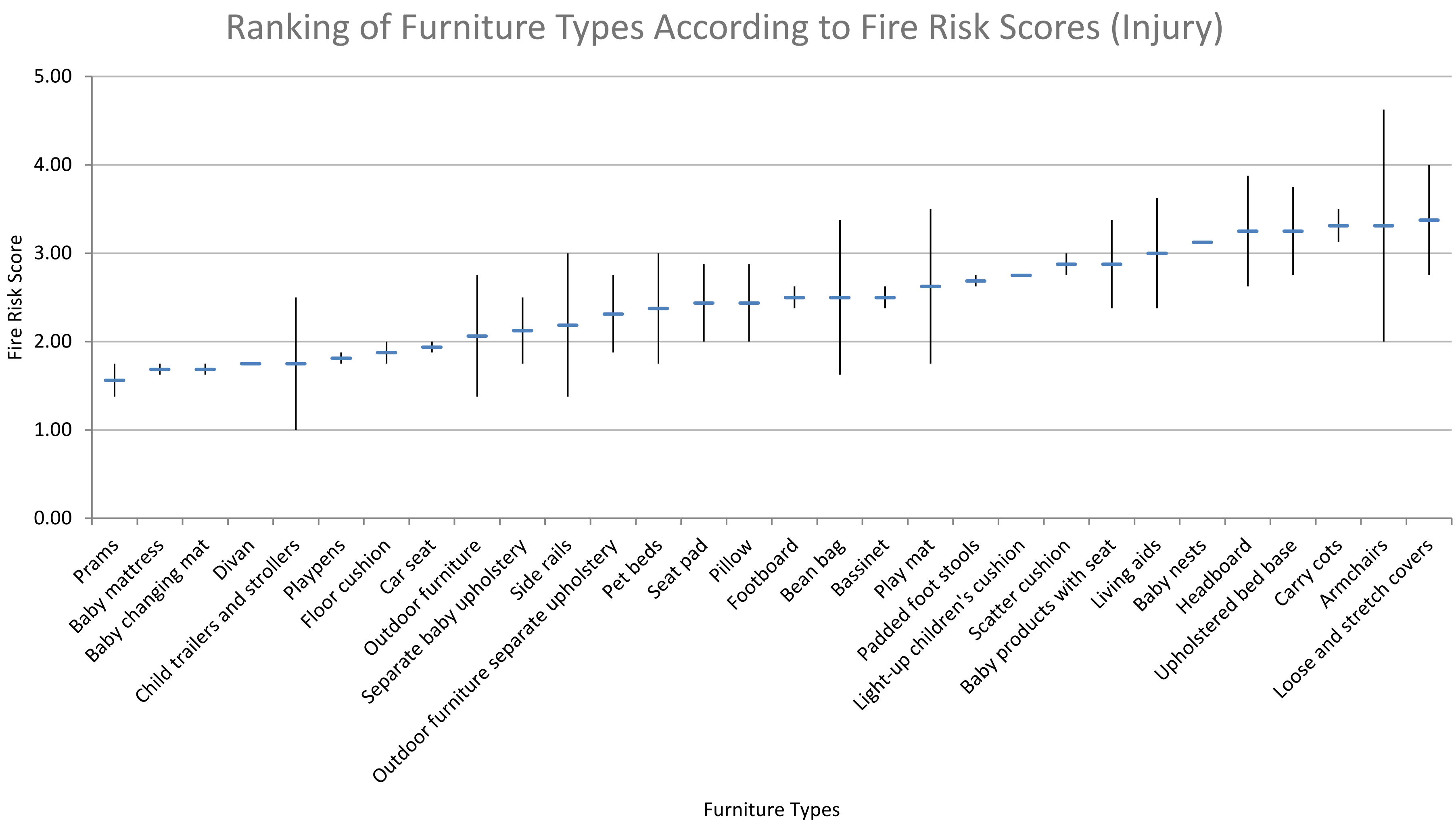


Figure 17 Ranking of furniture types according to risk of injury score. Ranking is made according to mean exposure score, with high and low scores shown as variance around the mean..

6.2.2 Fire retardant exposure scores

Table 19 shows the input data, domain scores, and FR exposure score for the FR exposure dimension of the matrix. The data for all 30 furniture product types are shown in the "Exposure Model Scores" sheet of Appendix 15 (furniture matrix data analysis).

Table 19 Input data and domain scores for exposure dimension of the risk matrix

Input data to the model

Ref No.	Furniture Type	Risk Variant	LRBW	Bare Skin	Mouthing	Duration	Surface Area
25	Baby changing mat	high	5	5	2	1	1.67
25	Baby changing mat	low	5	5	2	1	0.72
26	Pet beds	high	2	2	2	1	5.19
26	Pet beds	low	1	2	2	1	0.34
27	Outdoor furniture	high	2	5	2	3	14.85
27	Outdoor furniture	low	1	2	2	2	0.28
28	Outdoor furniture separate upholstery	high	3	3	3	3	0.91
28	Outdoor furniture separate upholstery	low	2	2	4	3	0.33
29	Living aids	high	1	4	2	5	3.34
29	Living aids	low	1	1	4	3	0.64
30	Armchairs	high	2	3	2	5	6.74
30	Armchairs	low	3	2	1	1	0.26

Transformation of surface area to size; scores integrated to create exposure scor

Ref No.	Furniture Type	Risk Variant	LRBW	Bare Skin	Mouthing	Duration	Size of Furnishing	Integrated Exposure Score
25	Baby changing mat	high	5	5	2	1	3	3.2
25	Baby changing mat	low	5	5	2	1	2	3
26	Pet beds	high	2	2	2	1	4	2.2
26	Pet beds	low	1	2	2	1	2	1.6
27	Outdoor furniture	high	2	5	2	3	5	3.4
27	Outdoor furniture	low	1	2	2	2	1	1.6
28	Outdoor furniture separate upholstery	high	3	3	3	3	2	2.8
28	Outdoor furniture separate upholstery	low	2	2	4	3	2	2.6
29	Living aids	high	1	4	2	5	4	3.2
29	Living aids	low	1	1	4	3	1	2
30	Armchairs	high	2	3	2	5	3	3
30	Armchairs	low	3	2	1	1	2	1.8

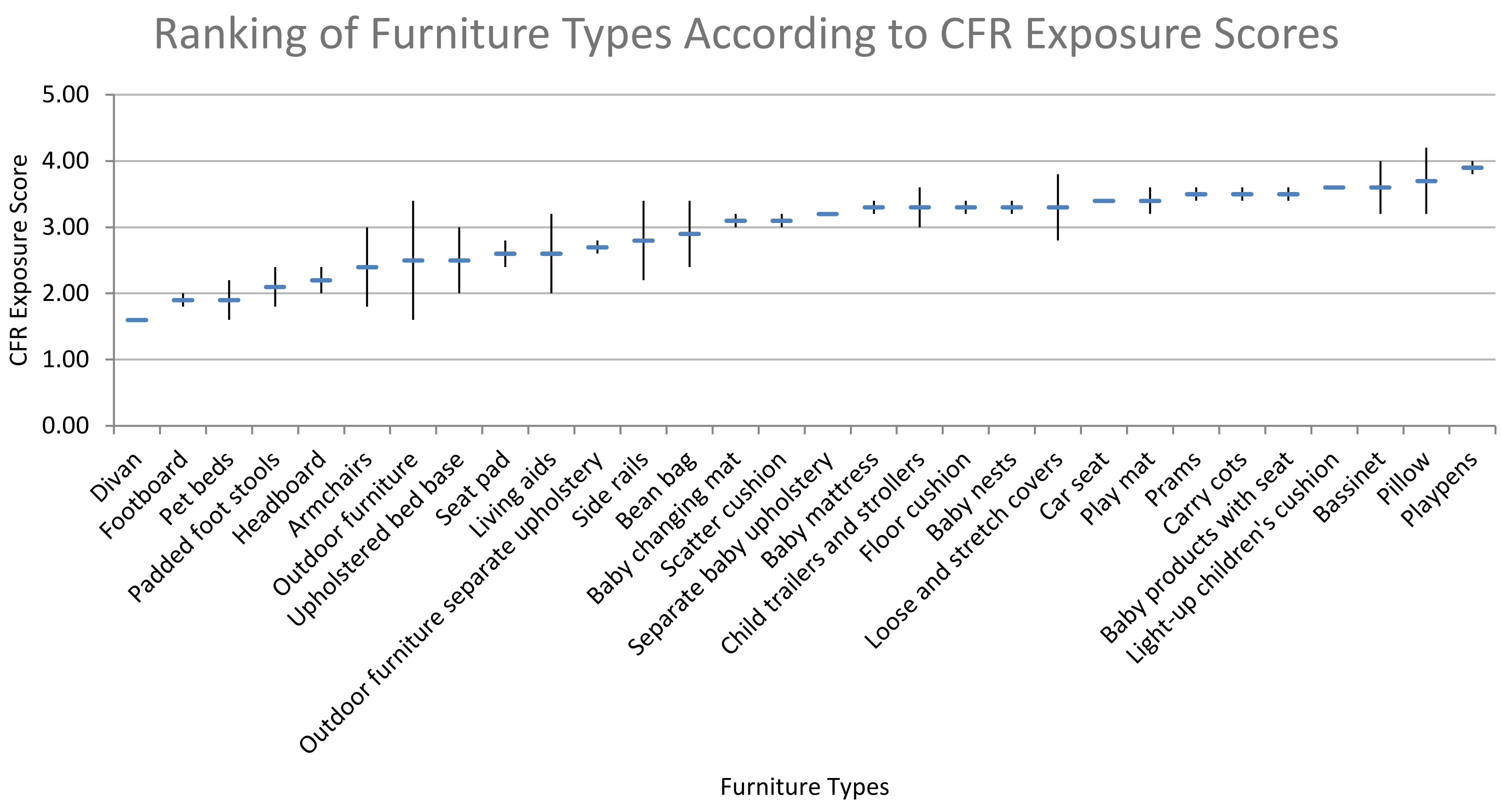


Figure 18. Ranking of furniture types according to potential exposure to fire retardants. Ranking is made according to mean exposure score, with high and low scores shown as variance around the mean.

6.3 Sensitivity of the matrix to evaluator error

Since a significant proportion of the data being used for the matrix is based on subjective judgement, and such judgements can potentially vary between individuals and may systematically differ between different groups, we tested the sensitivity of the results of the risk matrix to variation in evaluator judgement. The most important domain for sensitivity analysis is likelihood of contact of a furniture product type with an ignition source. This is a judgement that could be significantly shaped by professional experience, due to which intuitions about likelihood may differ to the general population. The remaining judgements are less likely to be sensitive to professional exposure, with e.g. likelihood of mouthing and reactive capacity of a user being arguably evaluable by non-experts.

There were two steps to our approach to assessing sensitivity of the matrix. In the first stage, we modelled the effect that systematic error in the contact domain would have on overall fire risk scores; in the second stage, we checked the evaluations of the research team against a sample set of evaluations by external experts, to see if foreseeable error was within the tolerances identified by our model in the first stage.

For the sensitivity model, we assumed that contact scores for each evaluated item (n=60, with a high and low variant for each furniture product type) were underestimated by 1 point, 2 points, etc., capping the maximum error at a score of 5. We plotted all the injury scores for each item of furniture against imputed error, adding a small amount of random jitter to each point so relative position could be seen on the plot. This produced the plot shown in Figure 19 (see Appendix 19 for source file). The plot shows that, even with a 2-point error in judgement, clear clustering can still be observed. Since the overall model is only aiming to differentiate furniture product types by relative fire risk and potential for exposure, the preservation of clustering indicates that the model is still successfully differentiating risk even in the presence of a reasonably significant degree of systematic error in evaluations.

Members of the BEIS-OPSS project advisory panel with fire investigation experience were asked to complete the evaluation questionnaire for a subsample of the furniture product types (armchairs, pushchairs, headboards, and pet beds) to determine whether the judgements made by the evaluators on the research team were consistent with judgements made by other experts. The results of this exercise are shown in Table 20. For the contact domain, in general the research team were more conservative in their judgements than the external evaluators, and the difference between the evaluations was within range of the tolerances indicated by the sensitivity analysis.

For other domains, judgements often differed significantly; however, the reasons for this were often to do with incorrect interpretation of a question (e.g. basing evaluations of ornateness on constituent materials) and sometimes internally inconsistent (e.g. scoring an armchair differently to a headboard, while stating that both could be used by a person who is asleep and has physical disabilities). Such issues are likely the result of the external evaluators not going through the training or consolidation process that the research team followed, which helps secure agreement on how to interpret a question and improves the consistency of evaluation.

Figure 19: Chart showing how injury scores for the risk of injury from fire change under systematic error in evaluation of the “contact” domain. Clustering is robust up to an error of 2 points.

Table 20 Table showing the results of evaluation by external experts of a subsample of furniture product types included in this report, compared with the consolidated scores used as the data for the fire risk model. The contact scores are within range of the limits determined by the sensitivity analysis.

Ref No.	Furniture Type	Risk Variant	Evaluator	Contact with Ignition Source	Number of Junctions	Ornateness	Reactivity of Person
30	Armchair	High	Consolidated	5	3	3	5
			1	4	3	1	5
			2	4	3	2	4
			3	4	5	4	4
		Low	Consolidated	3	1	2	2
			1	1	1	1	1
			2	2	1	2	1
			3	3	1	3	1
1	Headboard	High	Consolidated	4	3	3	4
			1	3	1	3	3
			2	2	0	2	2
			3	4	0	5	1
		Low	Consolidated	3	1	1	4
			1	1	1	1	3
			2	2	0	1	2
			3	4	0	3	1
14	Pushchair	High	Consolidated	1	12	4	3
			1	2	6	3	1
			2	2	6	4	2
			3	2	6	5	
		Low	Consolidated	1	3	3	3
			1	2	3	3	1
			2	2	1	3	2
			3	3	3	2	
26	Pet bed	High	Consolidated	4	3	2	3
			1	1	1	1	1
			2	1	1	1	1
			3	2	1	4	2
		Low	Consolidated	3	0	1	2
			1	1	0	1	1
			2	0	0	0	1
			3	3	4	3	2

7. Conclusions, limitations and future research

7.1 Conclusions

“The project had the following objective[xvi]:

“Research is required to build the evidence base to help inform policy proposals by determining whether certain articles/products represent a significant fire risk based on the product type.

“This will be achieved using the following outputs from the research:

1. A systematic review of products identifying holistic hazards and risks associated with fire safety of furniture (risk of catching fire, fuel load and risk of fire spread, chemical exposure from flame retardants, vulnerability of users)
2. An assessment of risk factors and weighting criteria for product types to be considered for inclusion/exclusion in the policy summarising the systematic review of evidence

“Expected outcomes from the research:

“This research will inform policy proposals on if the products should be excluded from the new approach to furniture fire safety. It is proposed that there is an exclusion list for products who will not fall within the scope and that for manufacturers of these products there they are not required to meet this regulatory burden. Excluded products must comply with the General Product Safety Regulations (GPSR) and will still need to be safe. A balance must be struck between keeping high standards of fire safety and reducing exposure to chemical flame retardants. It is important that products within scope meet and continue to improve on the UK fire safety levels.

1. Strengthen evidence base on furniture fire safety
2. Collate cross-disciplinary evidence on fire safety and chemical exposure in a systematic review
3. Inform options for policy proposal for what products should, or should not, be in scope based on existing evidence
4. Resolve outstanding issues raised in existing research, which focus on the risks of chemical exposure to flame retardants versus the risk of products catching, and spreading, fires
5. If needed suggest areas for further research”

The report summarises key evidence which can be used to inform policy proposals relating to revision of the FFFSRs. Information is presented on: fire statistics, in an attempt to establish the extent to which individual furniture product types contributed to serious fires; descriptions of fire retardant strategies, and the chemical flame retardants (CFRs) currently adopted for making furniture compliant with the FFFSRs in order to distinguish between those CFRs currently in use, but similar to those currently being restricted, and others which may be more suitable as safer replacements; and the potential contribution of furniture derived CFRs to the presence of these compounds in UK indoor environments.

An objective of the research was to contribute to evidence base with which BEIS-OPSS could include or exclude certain product types for example scatter cushions, garden furniture, playpens etc.

Detailed fire statistics for England show that most fires and most fire fatalities occur in dwellings. While most dwelling fires start in kitchens, most fire fatalities occur in fires that started in living/dining rooms and bedrooms. Most people who die in fires are very old (~25% of fatalities are 80 or over), or old (~25% are 65-79). Most fire fatalities and most fire injuries result from inhalation of toxic smoke.

[xvi] Taken from the Invitation to Quote document issued by BEIS-OPSS

England's fire statistics report that upholstered furniture was the *material or item first ignited* in 1.5% of domestic fire incidents and 9% of fire fatalities; it was the *main material responsible for fire development* in 2% of fires and 15% of fire fatalities. Similarly, beds/mattresses were the *material or item first ignited* in 1.5% of domestic fire incidents and 6% of fire fatalities; they were the *main material responsible for fire development* in 2% of fires and 11% of fire fatalities. Taken collectively, the contribution of beds, mattresses and upholstered furniture in dwelling fire fatalities as the material or item first ignited was 15% and as the main fuel in fire development was 25%. The current FFFSRs require resistance to small ignition sources, such as a cigarette, match or 4 sheets of newspaper. In contrast, contract furniture in pubs, hotels and offices requires a higher level of ignition resistance, equivalent to burning a child's comic. This shows that compliance with the FFFSRs is aimed at suppressing ignition, but not retarding fire development.

The term "chemical flame retardant" (CFR) implies a homogeneous group of synthetic chemicals. CFRs range from naturally occurring minerals, cellulose and lignin (products derived from wood), to synthetic inorganic and organic chemicals. Some of the organic CFRs have proved to be persistent, bioaccumulative and toxic (PBT). These include halogenated and organophosphorus compounds. The very high levels of certain CFRs detected in the UK and Irish environments have been raised as a cause for concern by the UK Committee on Toxicity[59]. The adverse health impact of brominated CFR exposure includes impaired neurological development, based on their toxicity in animal studies to the liver, thyroid hormone homeostasis, and the reproductive and nervous systems[60], while organophosphates have been found to be reproductive toxins and have carcinogenic, neurotoxic, and endocrine-disrupting properties[102]. The main CFRs used in furniture foam, organophosphate esters, are currently under scrutiny by the European Chemicals Agency.

The second part of the project focuses on developing a furniture fire safety risk matrix tool in order to assess peripheral furniture product types (cushions, pillows, baby products, garden furniture etc.), with a view to including or excluding whole furniture product types from the new furniture flammability regulations.

Ideally, statistical data from fire incidents would provide robust data to inform such a process. Unfortunately, the nature of unwanted fires prevents that information from existing. Accidental ignition is rarely observed, and when it is, simple actions are undertaken to extinguish and prevent fire spread. Once the fire has grown out of control, the material or item first ignited and the source of ignition may not be identified unambiguously, and be assigned, based on informed speculation. Serious fires destroy most of the evidence about their ignition and growth and even fuel involved. The limited data available suggests that it is not usually possible to unambiguously identify the items responsible for a fire's development, either the material or item first ignited or the material mainly responsible for fire development, or to access fire performance data relating to the range of items comprising each furniture product type

Nonetheless, all the peripheral furniture product types were reviewed, grouped and described, both in terms of physical parameters, and, with help from industry experts, the common approaches to achieving compliance with the FFFSRs.

In parallel to this assessment of physical and fire protection parameters, a thorough review of the literature was undertaken in order to create robust and defensible concept networks identifying the driving forces in ignition, fire development and potential hazards. These overarching concept networks were then analysed, with the support of expert opinion, in order to develop risk matrices.

To the best of our knowledge, this is the first time this type of approach has been applied to parameterising the significant fire and CFR exposure risks posed by furniture. It was valuable in that it allowed the empirical evidence base, i.e. scientific and other literature, to be analysed effectively and transparently. It uncovered the unevenness of concept coverage in the literature as well as providing the justification for our taking a more qualitative approach to ranking the furniture types than was originally intended.

The fire safety risk matrix assesses the parameters likely to lead to development of a serious fire (one likely to cause death, serious injury or significant property damage) but crucially which includes user behaviour and mobility as well as flammability. Understandably, the factors driving fatality, injury and property damage were sufficiently similar that assessment of injury risk covered all three potential threats. The CFR exposure risk matrix covered the parameters governing the likelihood of exposure to CFRs, based on users and their behaviour, absorption routes, geometry etc.

These two risk matrices have been combined into an overall furniture fire safety matrix, which is presented in Chapter 6. The matrix indicates that there are furniture types that present lower fire risk and higher potential for exposure, which may justify the reduction of use of CFRs in some of these types.

7.2 Strengths and Limitations of this Research

This study comprises two parts:

1. Assessment of the relative risks of fire and of exposure to CFRs: and
2. Creation of a furniture fire safety risk matrix tool to support decisions on inclusion or exclusion of particular furniture product types from the revised regulations.

The lack of available data relating to fire incidents: the destructive nature of fires destroys evidence relating to material or item first ignited and material mainly responsible for fire development, particularly in serious fires.

In an area in which empirical data is limited, we believe we have developed models and populated them with data that enables meaningful differentiation between types of domestic upholstered furniture based on anticipated fire risk and potential for CFR exposure. We achieved this by employing a mixed-methods approach, combining qualitative and quantitative methods to ground fire risk and CFR exposure models in the literature and expert opinion, in what we believe is a novel approach to risk modelling in the fire safety sciences. Our methodology allowed us to integrate behavioural factors (likelihood of contact with an ignition source) and user vulnerabilities (ability to react to a fire in an item) when modelling risk of injury or damage in relation to fire in furniture. We believe these are novel additions to fire risk models.

7.2.1 Availability of data and implications for improving furniture fire safety

While a wide range of risk concepts are discussed in reviews of furniture fire safety literature, only a small proportion have been the subject of significant empirical investigation as to the role they play in fire risk. Fabric, foam, and upholstery are the most-mentioned terms in the primary literature by some margin, and smokers materials are the most-studied source of ignition; however, the role of age and disability in risk of injury in fire is relatively unstudied (Appendix 9 Code List: “code thesaurus” and “Risk Term Frequency in Texts” sheets). In interview, fire investigators mentioned fuel poverty and drug or alcohol abuse as two major fire risk factors. The former results in fires due to accidents involving halogen heaters being used as a source of warmth that is cheap in comparison to central heating, the latter from erratic behaviour and vulnerability due to impaired situational awareness. This suggests there are specific vulnerable subpopulations that are beyond the level of resolution offered by our model (for example, it is possible that small child products are very low risk except in certain specific circumstances), and there are potentially important secondary sources of ignition (such as blankets igniting by being in very close proximity to halogen heaters) that are beyond the scope of our model.

7.2.2 Scope and interpretation of the models

The furniture fire safety matrix is designed to provide evidence to support policy decisions relating to the scope of the FFRs, based on anticipated CFR exposure and fire risk. Due to a lack of empirical data, it was necessary to model relative fire risk and relative potential for CFR exposure, based on data categories that could be expected to be reliably evaluated by informed persons. Low scores for exposure to CFRs from items of furniture should not, therefore, be interpreted as being of low potential concern. For example, headboards score relatively low, but may still pose an absolute level of CFR exposure that may be problematic. Furthermore, our model says nothing about what approaches ought to be taken to ensure that furniture is fire safe. Decisions about such approaches may need to account for the environmental or health implications of using potentially large quantities of CFRs to comply with fire safety tests, and the behaviour of furnishings in a fire, such as smoke opacity and toxic gas production. These are additional issues beyond the scope of our model.

7.3 Recommendations

Our main challenge was the time constraint we were working under to produce a functional model to support the revisions of the FFRs. This limited the amount of data we could collect and analyse, and the number of model assumptions that we could alter and test. We have provided baseline models for discussion, and a path forward for their development. We hope the level of detail we have provided in the methods and supplemental materials is sufficient to enable our models to be extended and/or modified.

7.3.1 Domain identification and selection

The concept networks show how lower-level fire risk and CFR exposure factors relate to higher-level factors, that the user can be confident is grounded in the literature and expert opinion, and provides a basis for an informed discussion about the level of granularity desired from the model. To develop the networks, more literature could be reviewed; however, we would instead recommend prioritising extension and reorganisation of the concept network with more expert input. In particular, this should include analysis of narrative text from fire investigation reports and more interviews with non-academic domain experts such as fire investigators. These are two sources of concepts to which we did not have significant access and may provide additional perspectives not found in the published literature. This could impact choices about domain selection, domain weighting, and data input categories.

7.3.2 Domain weighting and transformation functions

The relative weight of each domain in the models could be finessed. For fire risk, differences in criticality of failure mode could be incorporated into the model. For potential exposure to CFRs, not all dimensions will contribute equally to exposure. There might also be interactions between domains. It may be the case, for example, that size of item, dermal migration, and duration of contact is cumulatively more important relative to oral migration when it comes to CFR exposure. A large item of furniture, as a large reservoir of FRs, may also present a disproportionately large source of exposure. We log transformed surface areas so smaller changes are more important when the surface area is small, in order to improve differentiation and increase clustering; however, a different transformation function may be more appropriate, especially if the objective is to accurately model relative potential for CFR exposure independent of the clustering objective we had in the present study. Finding or generating empirical data that will support weighting decisions will be challenging.

7.3.3 Input data

Model scores could be made more precise and more generalisable if more evaluations were conducted, and if empirical data could either be located or generated for model dimensions.

Increasing the number of evaluations: Increasing the number of evaluators involved in providing input data for data categories that involve subjective judgement would give a clearer indication of spread of subjective judgements. This would at least reduce uncertainty in the model due to potential variance in evaluator judgements, and it may increase precision of the model. Evaluating more types of furniture would present a more complete picture of the whole furniture landscape and could result in more robust clustering and/or extension of an identified cluster to other furniture types. Evaluating more items of furniture within a type would improve the precision of the model for each type. When increasing the number of evaluations, researchers should be aware that the evaluation process is time-intensive. Our training and consolidation process was designed to compensate for the small number of evaluators; increasing the number of evaluations without training may generate noisy data that does not improve the model.

Adding empirical data: Direct, empirical data for each domain could be generated through new primary studies or potentially derived from the literature, if available from a source that we did not identify or did not have capacity to analyse. Data on frequency of contact of furniture with ignition sources, and understanding the ignition source type (e.g. primary or secondary ignition source) could be especially useful for the model and informing risk management decisions, as would the role of the ability of people to react to a fire in relation to an item of furniture in understanding risk. Tracing CFR exposure back to specific types of furniture would improve the exposure model but may be difficult to achieve.

8. Annex 1 Analysis of Fire Statistics

The data in Annex 1 have been extracted from government statistical reports, based on data provided by the individual FRSs. Early data are from Fire Research Station reports with the role being taken over by central government in 1974.

In 1994 the Fire Data Report (FDR) was introduced. This was initially a paper-based report which sought to gather a significant amount of valuable information about primary fires. Primary fires include all fires in buildings, vehicles and outdoor structures or any fire involving casualties or rescues or fires attended by five or more fire appliances. In April 2009 the computer-based Incident Recording System (IRS) was introduced by the then Department for Communities and Local Government (DCLG), with this system currently being used by all FRSs in Great Britain, enabling the gathering of more detailed information on incidents attended by an FRS.

Fire location data was not recorded prior to 1970. Before 1981, the two categories of Outdoors (Road Vehicles) and Outdoors (Other) were grouped together as 'Outdoors'. Since 1999 fire statistical reports place the location of the fire into one of four categories: -

• Dwellings – e.g. residential homes, and houses in multiple occupation (HMOs)
• Other Buildings – e.g. B&Bs, halls of residence, offices, shops, factories, public buildings etc.
• Road Vehicles
• Other Outdoors – e.g. fields, woodland and derelict vehicles/buildings

A1.1.1 Causes of fire deaths and injuries

The cause of a fire fatality (referred to as fire-related fatalities in Home Office statistics) is categorised as follows:

- Burns – where there is evidence of severe burns, but high levels of carboxyhaemoglobin (COHb) in the victim's blood could not be found.
- Overcome by gas/smoke – where there are high levels of COHb and little evidence of life-threatening burns.
- Burns and overcome by gas/smoke – where there are severe burns and high levels of COHb and the pathologist considers that both were contributory towards the cause of death. This is often unclear. Toxic gas inhalation ceases when death occurs, whereas burn injury continues.
- Other – this category is used for fire deaths with other causes (e.g. injury resulting from escape).
- Unspecified – where an incident is subject to an ongoing investigation, the coroner may record an unspecified cause, and this may not have been subsequently updated.

In many cases the severity of the fire will destroy evidence which could otherwise help to identify the cause of death.

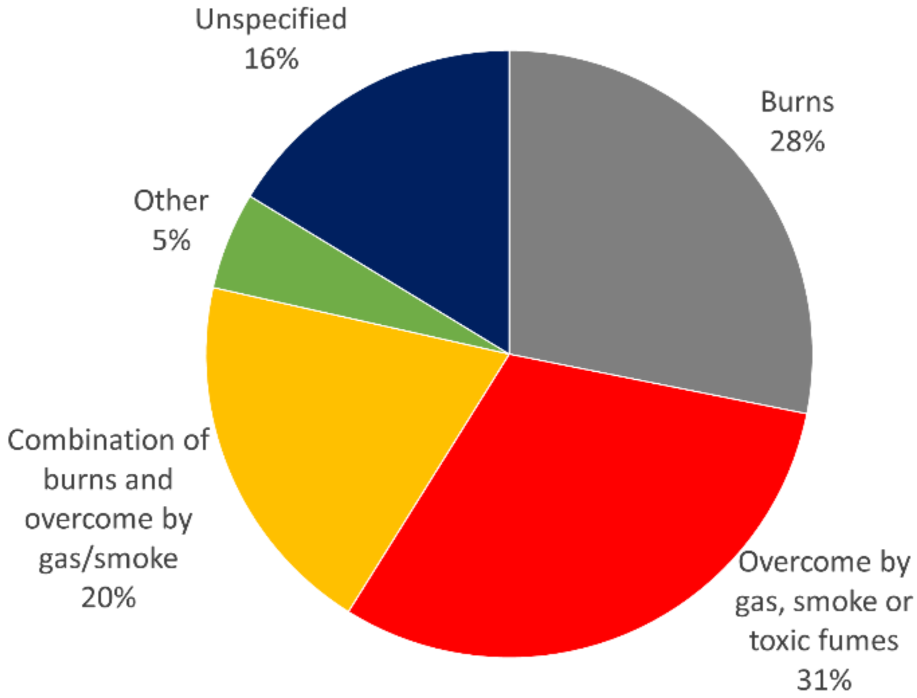


Figure 20 The cause of fatalities from fires in Great Britain 2019/20 (using data downloaded in Aug 2021 from ref 75)

Figure 20 shows the Great Britain fire fatalities by cause of death, using the classifications above. This shows the importance of smoke toxicity in around half of all fire deaths[75]. Eventually, "Unspecified" fire fatalities are likely fall proportionately into one of the other four categories. The analysis has therefore been repeated as shown in Figure 21. This shows that 23% of fire-related fatalities are caused by smoke inhalation alone, 37% are caused by burns and the remaining 40% are either split between "burns" and "other".

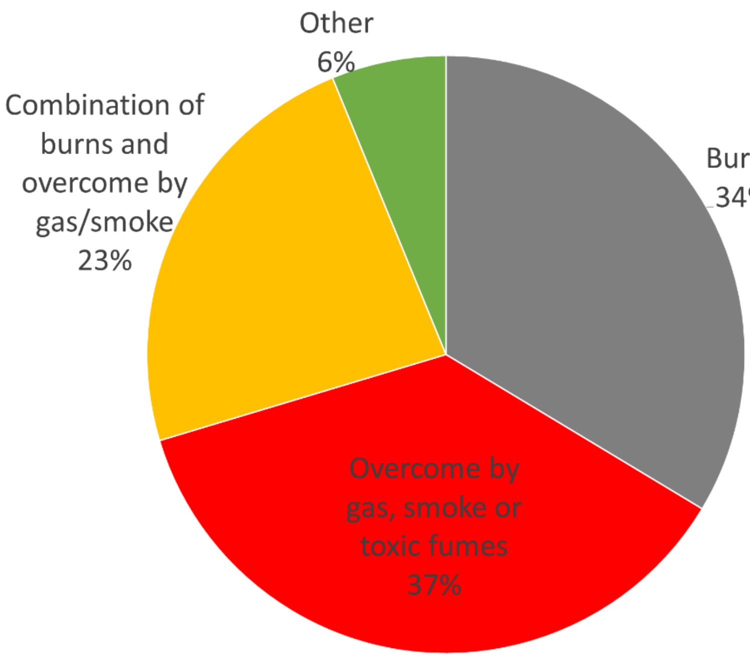


Figure 21 Fire fatalities by cause of death, Great Britain, 2019/20 (adapted as described above),

Figure 22 shows the time series data for cause of death from 1955 to 2019. The increase in fire deaths from 1955 to 1980 corresponds to the widespread replacement of natural materials, such as wood, cotton and wool with synthetic plastics[76]. The increase in smoke toxicity deaths corresponds to the increased use, and greater flammability and smoke toxicity, of polymeric materials, and possibly polymeric materials incorporating gas phase flame retardants (see Annex 2).

Thus, smoke inhalation is one of the major causes of fatal casualties, resulting in at least 40% of deaths.

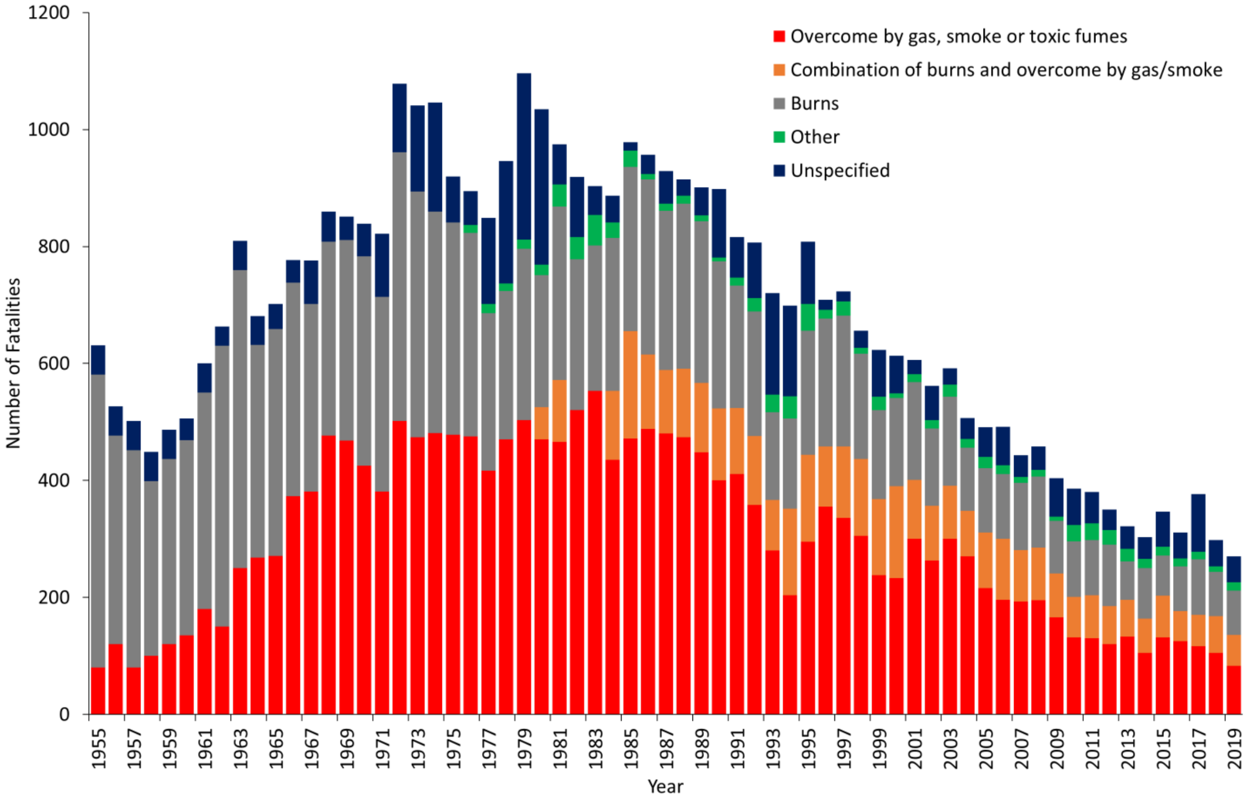


Figure 22 GB Fire fatalities for all incident locations by cause of death, data from ref 75. A new category of combination of burns and overcome by gas/smoke was introduced in 1980. (Grenfell fatalities are shown in 2017 as "unspecified", as they are awaiting the coroner's verdict).

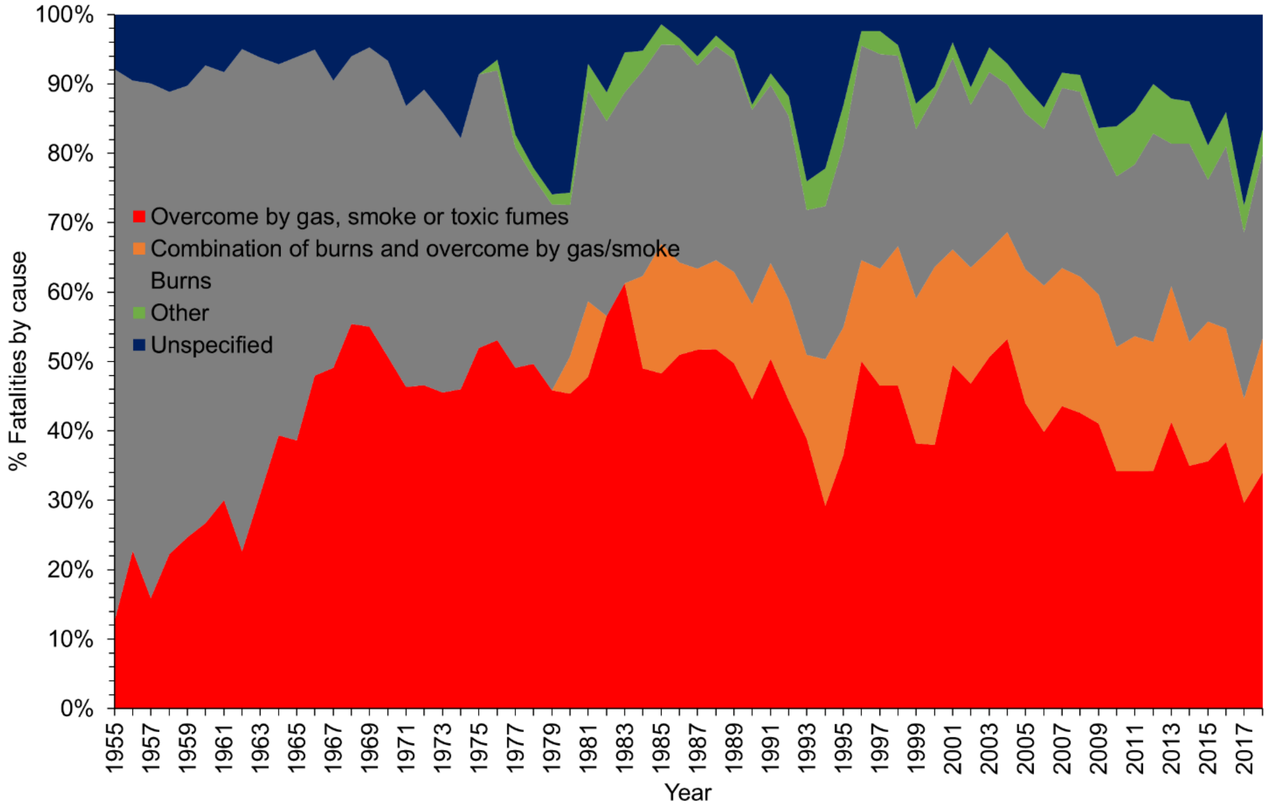


Figure 23 Great Britain fire fatalities for all incident locations by cause of death, as % of total fatalities (data from ref 75)

In Great Britain, and also in the United States[77], most injuries in fires are also due to inhalation of toxic smoke, as shown in Figure 24 for all fires in Great Britain[75] in 2019/20. Recently, an additional category of non-fatal casualties are reported as *precautionary check-up*, implying that no injury was found, which, aside from the trauma, could be considered a positive outcome. As this is now the largest fire injury classification group at around 47% of total non-fatal casualties, precautionary check-ups have been removed from the reported injury data. This makes overcome by gas, smoke and toxic fumes the major contributor to non-fatal casualties resulting in 51% of injuries in 2019-20.

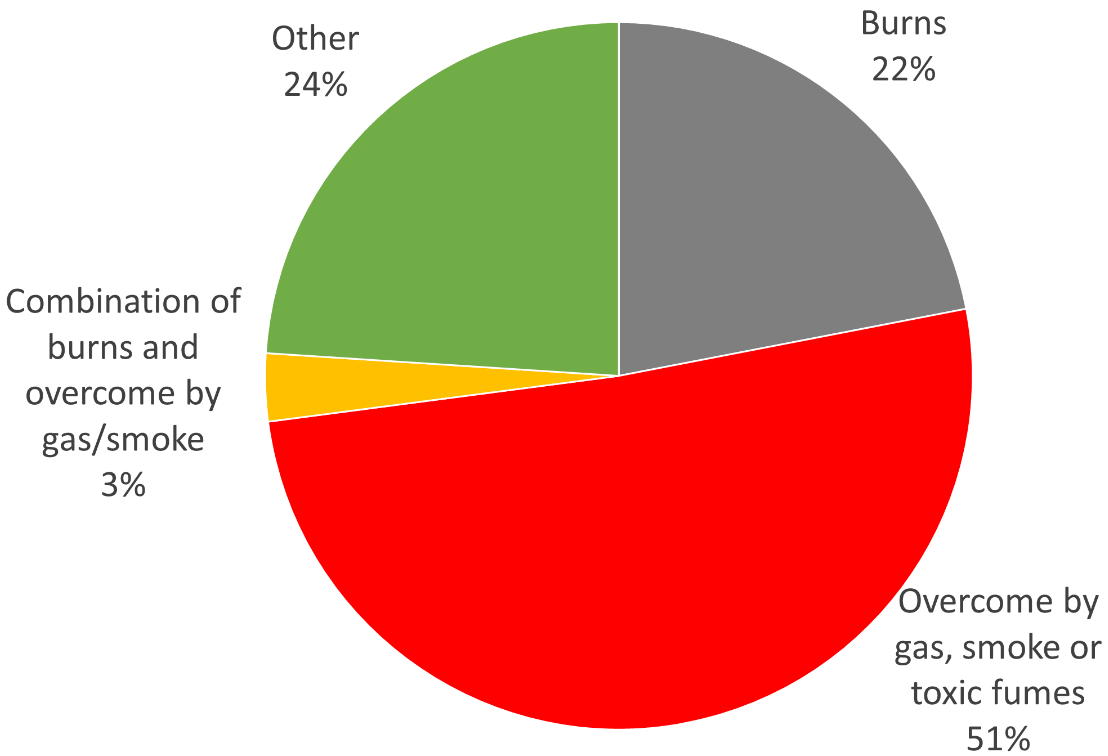


Figure 24 Non-fatal casualties by nature of injury, Great Britain, 2019/20 (data from ref 75)

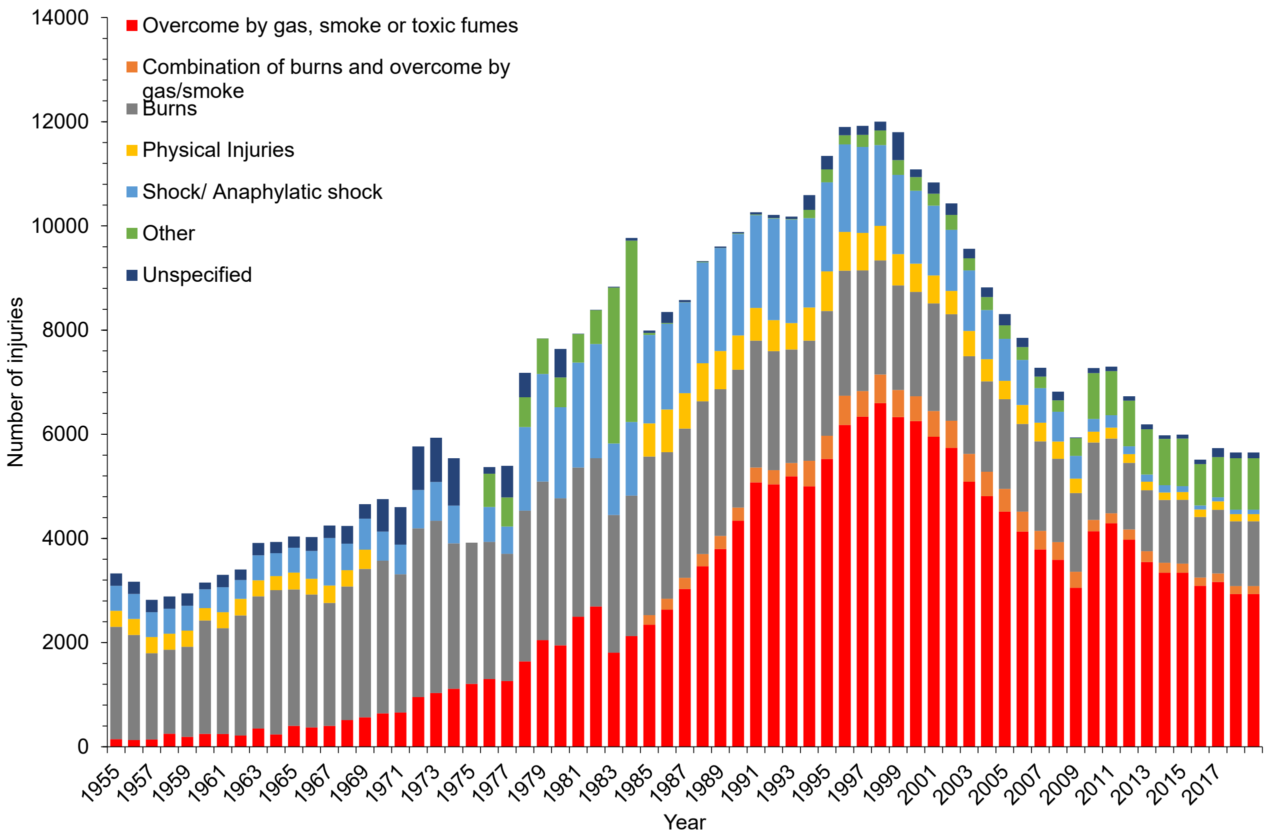


Figure 25 Nature of GB fire injuries for all incident locations from 1955 to 2019 (data taken from ref 75).

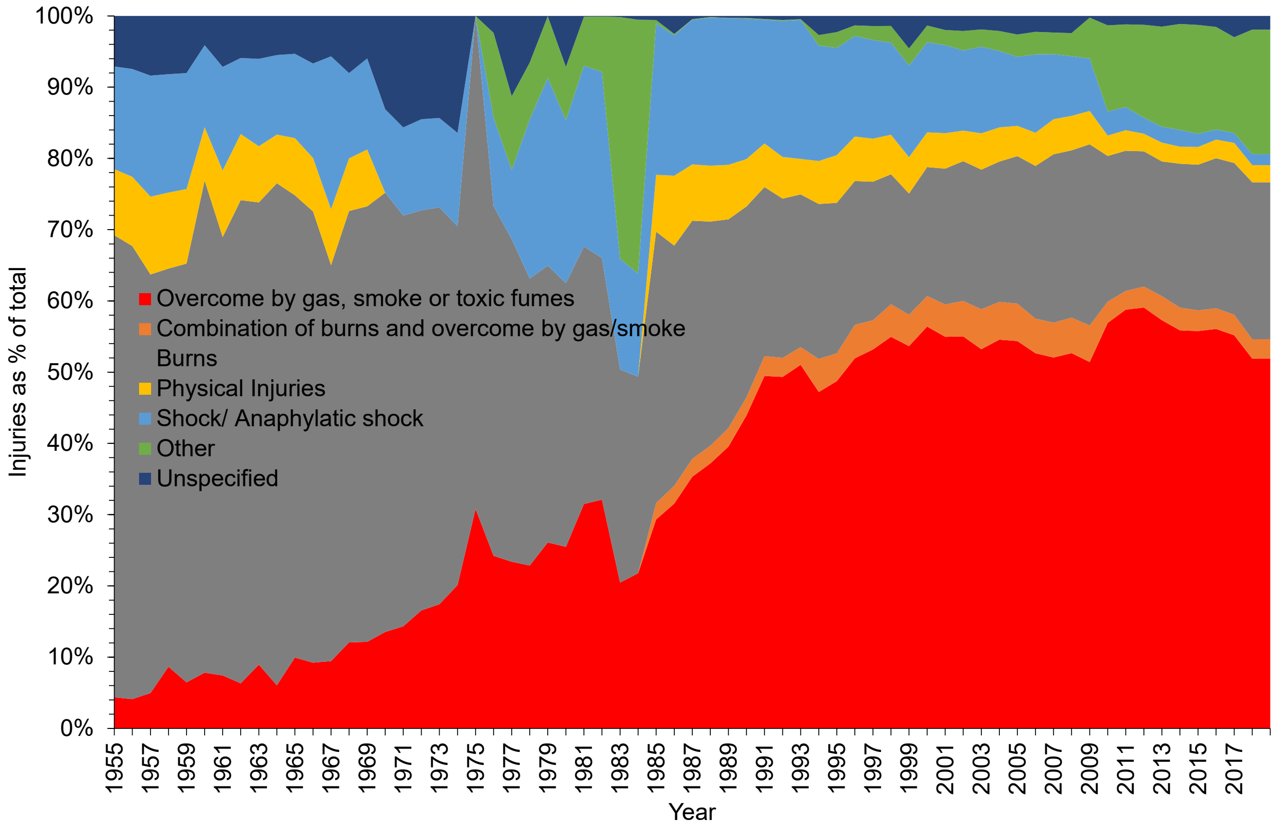


Figure 26 Nature of GB fire injuries for all incident locations as % of total from 1955 to 2019 (data from ref 75).

A1.1.2 Comparison fire death rates in the UK and similar countries

The age-standardised fire death rates in the UK and those of similar countries[78] are shown in Figure 27. This shows a progressive downward trend in fire deaths across those countries. However, such comparisons have limitations, as many factors are involved (including data recording policies, cigarette smoking habits, use of open flame heating, deployment of smoke detectors etc).

A detailed study produced for the European Commission[79] on the risks and benefits of adding fire retardants to furniture, analysed the fire fatality data from individual European countries with different levels of flammability regulation. While the study acknowledged the difficulty in comparing statistics from different countries, it concluded that "*in some instances, drops in the number of fire deaths coincide with the introduction of non-flammability requirements for domestic consumer products. In other instances, however, there is no change in the on-going trend of fire deaths. This suggests that these numbers do not reflect the stringency of non-flammability requirements, respectively that non-flammability requirements do not visibly decrease the number of fire deaths*."

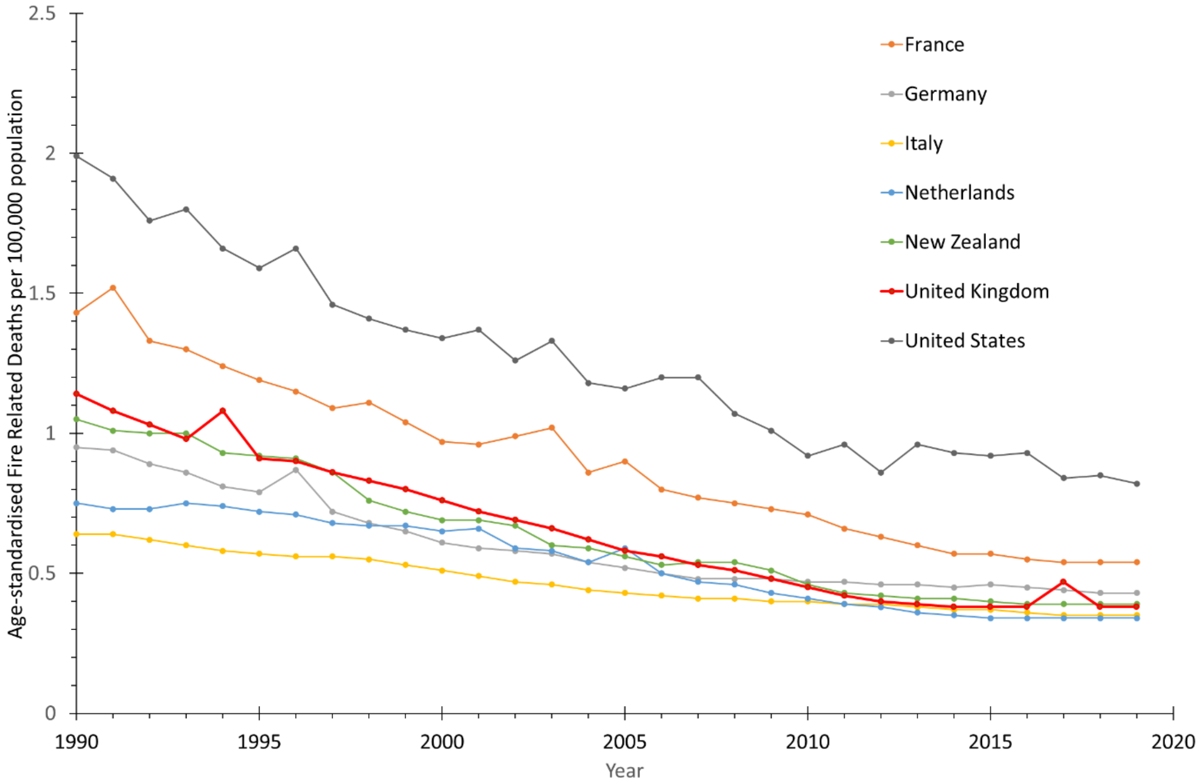


Figure 27 Age-standardised fire deaths per 100 000 population in UK and in other developed countries (data taken from ref 78).

A1.2 Detailed Fire Statistics for England

Until 2015 fire statistics were reported for Great Britain. Since 2015, fire statistics have been reported separately for England, Scotland and Wales. The data are reported in slightly different formats, so the analysis in this section has been limited to English data for consistency. An analysis of fire statistics has been undertaken to establish the importance of upholstery in respect of both fire-related fatalities and non-fatal fire casualties. All the relevant data were downloaded when the analysis was carried out in August 2021. The most recent data covering the first year of the COVID pandemic has not been included: it was not available when the report was first drafted; and it is considered unrepresentative of "normal" times.

A1.2.1 Fire Fatalities by location

The majority of fire-related fatalities occur in dwellings and have consistently accounted for around three-quarters (77%) of those deaths over the last ten years (Figure 28). Over the same time period, only 6% of fatalities occurred in other buildings, with 10% in road vehicles and 7% elsewhere outdoors.

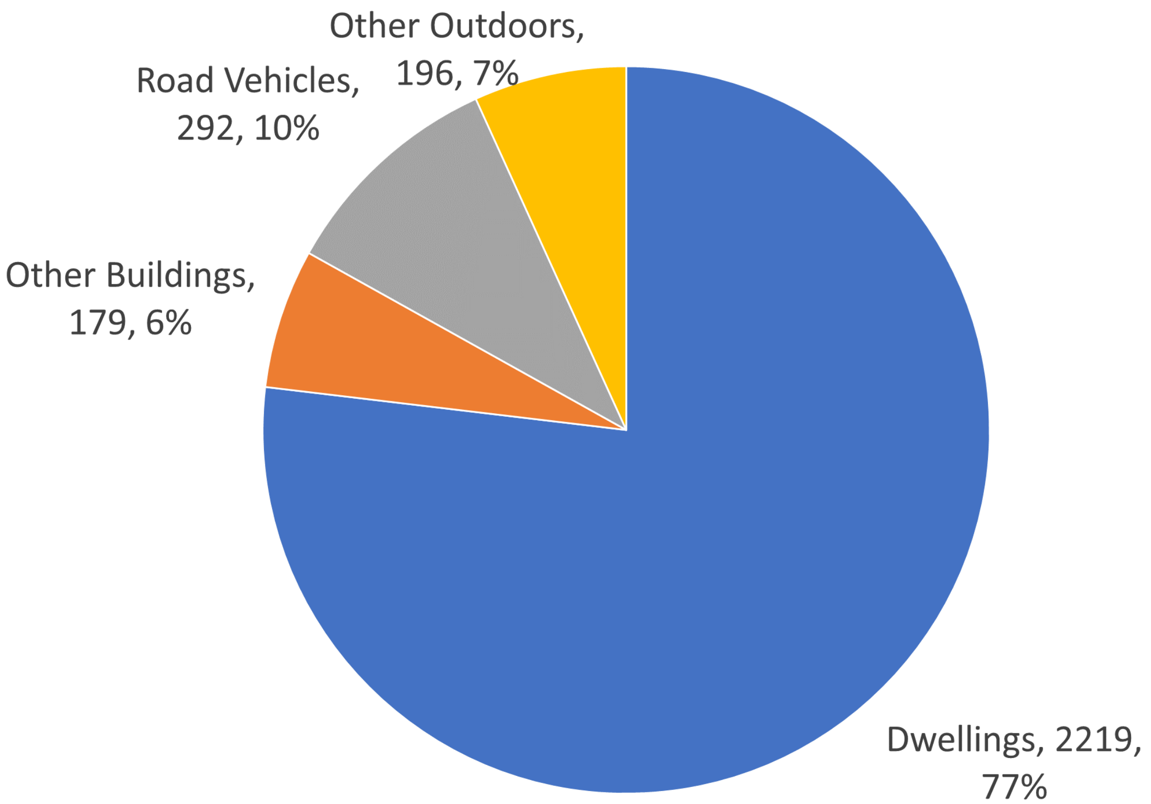


Figure 28 Location of fire-related fatalities, England, as total deaths and percentage, combined data for 2010/11 to 2019/20.

Analyses of the data over the same period shows that dwelling fires also contribute 77% of the total of non-fatal casualties.

A1.2.2 Fire fatalities by age of victim

The age group each fire fatality victim belonged to is shown for dwelling fire victims in Figure 29 as actual numbers and as a percentage of the total dwelling fire fatalities in England from 2010-20. The total number of dwelling fire fatalities was 2219.

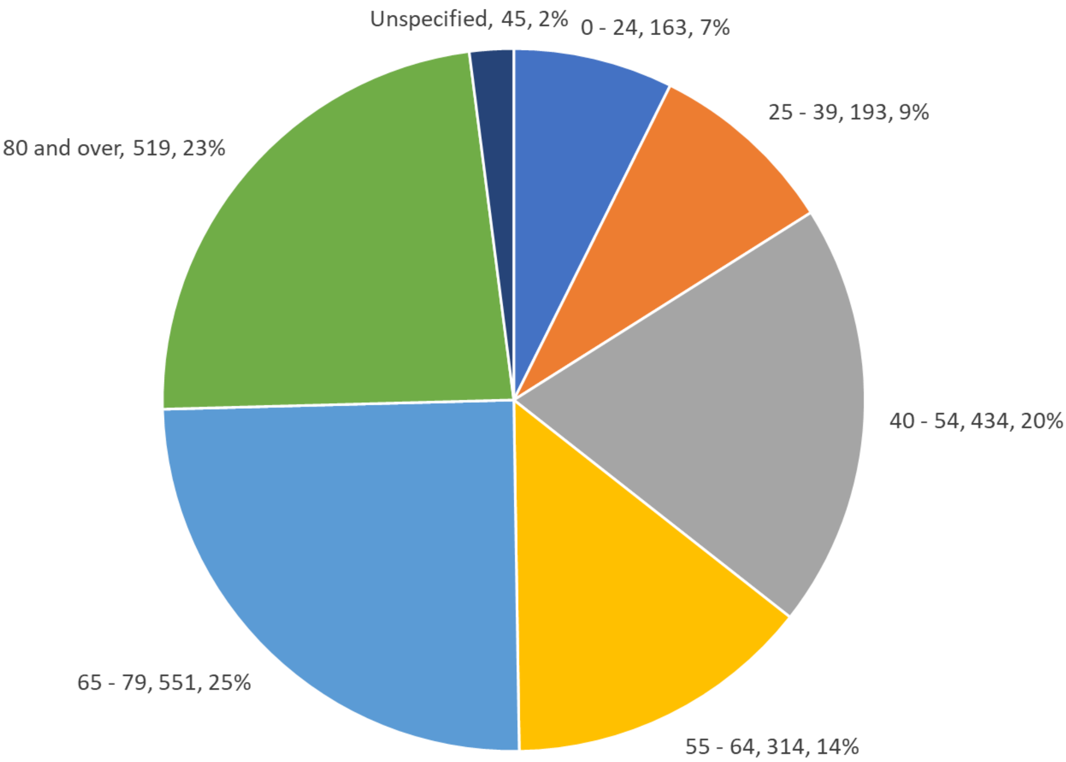


Figure 29 Age range of dwelling fire fatalities, England, as total deaths and percentages, combined data for 2010/11 to 2019/20 . Numbers for younger age ranges: under 1 = 6; 1 – 5 = 42; 6 – 10 = 42; 11 – 16 =21; 17 – 24 = 52.

However, this data does not tell the whole story, as, for example, the proportion of the population aged 80 and over is much smaller than for younger age groups. The number of fatalities per million population of that age range shows more sharply how fire disproportionately affects the elderly. These are shown as percentages in Figure 30.

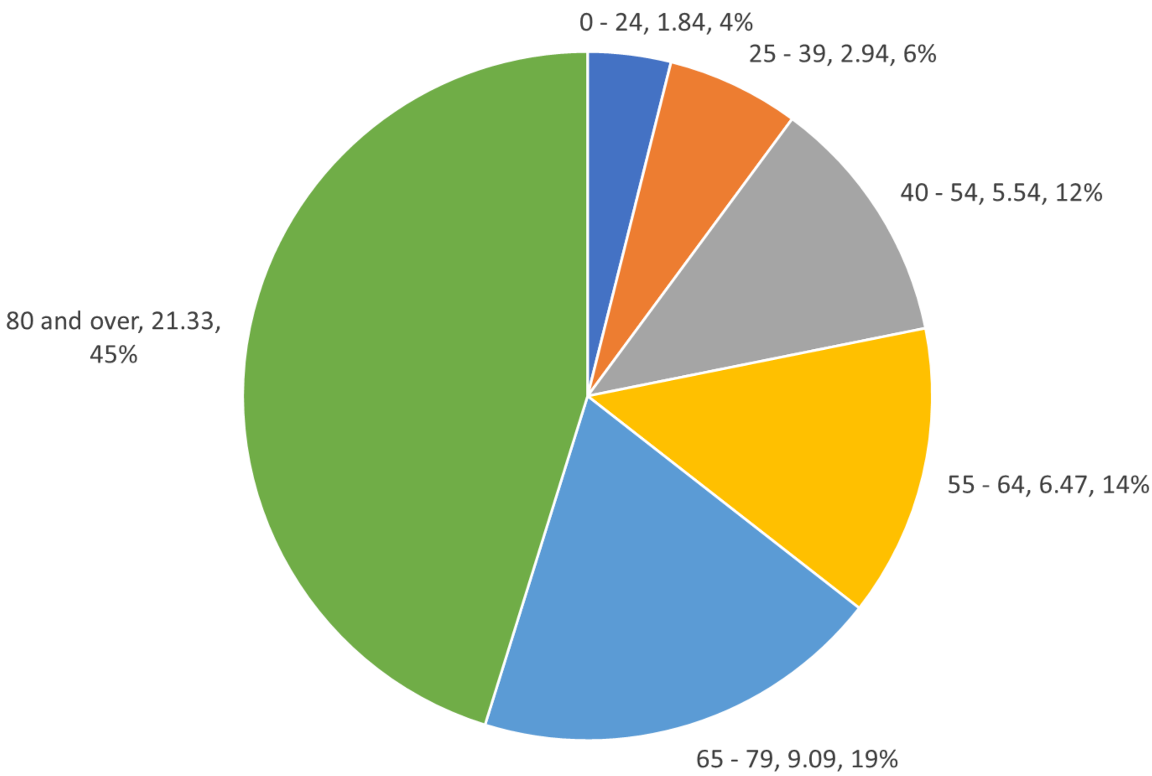


Figure 30 Number of fatalities per million population and percentage of total for dwelling fires, England, as total deaths and percentages, combined data for 2010/11 to 2019/20 .

A1.2.3 Fire fatalities by time of day

Figure 31 shows the frequency of fire incidents and fatalities from accidental dwelling fires as a function of time of day. The fire incident frequency could be predicted from typical behaviour patterns. However, the fatality frequency is high in very early morning (or “middle of the night”), early morning and late evening (the peak at midnight to 1 am is greatest because of an additional 71 Grenfell Tower fatalities). This shows that the frequency of fire fatalities is not closely linked to fire incident frequencies.

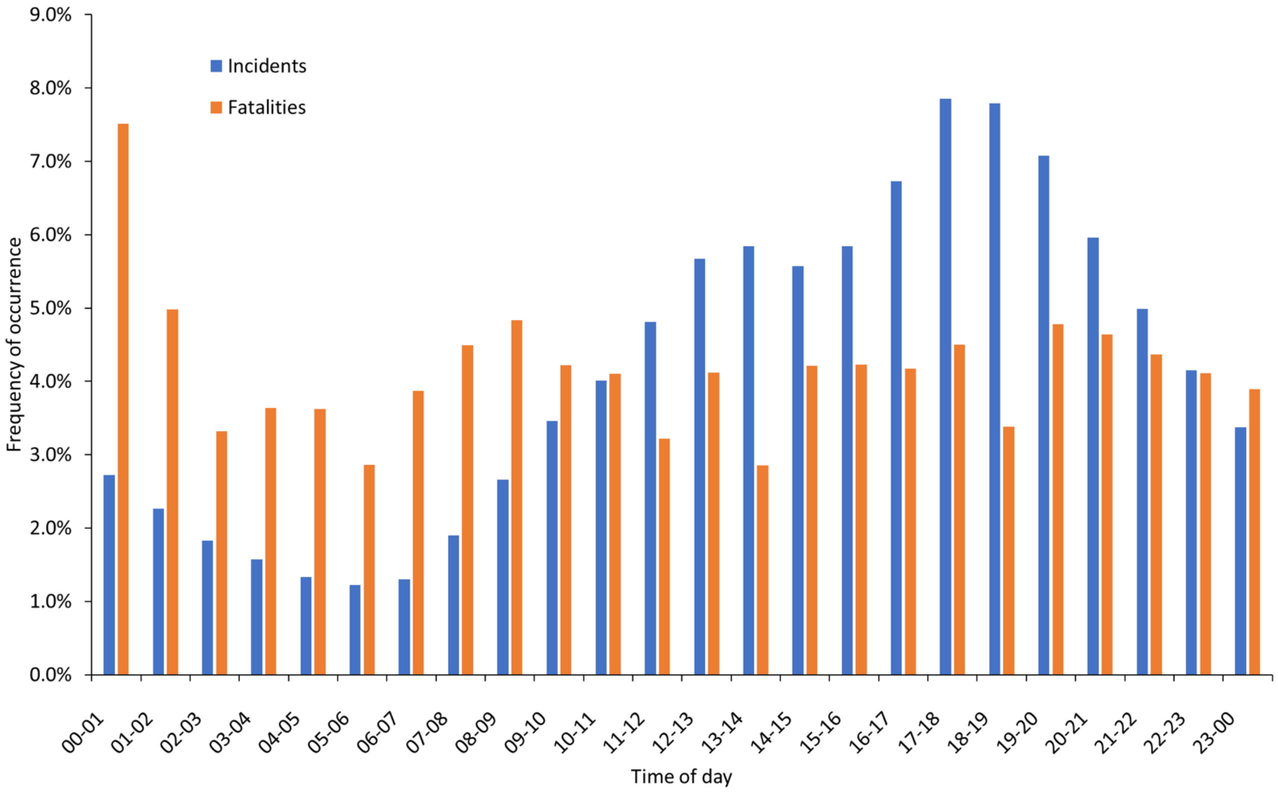


Figure 31 Frequency of accidental dwelling fire incidents and fatalities, by time of day, 2010-20. Note that if the Grenfell fatalities are excluded, the percentage fatality from 00-01 falls from 7.5 to 4.6.

A1.2.4 Location of dwelling fires and fatalities

The project was limited in scope to fires involving upholstered furniture occurring in the home, and it has been shown that most fire fatalities occur in dwellings. Therefore, the following discussion relates only to dwelling fires. Over the last 10 years (2010-2020) FRSs attended a total of 319 223 dwelling fires in England resulting in 2 219 fatalities and 60 579 non-fatal casualties. The number of dwelling fires has decreased from 36 611 in 2010/11 to 28 447 in 2019/20[80]. A much smaller number of these fires were severe, with around 13% spreading beyond the room of fire origin. For example, of the 28 447 dwelling fires in 2019/20, 9 212 of these fires were limited to the material or item first ignited and a further 6 924 were limited to the room of fire origin, with only 3 677 spreading further. The average area of fire damage was 16.5 m^2. These fires resulted in 200 fatalities and 5 154 injuries in 2019/20, having fallen from 255 and 7 498 respectively in 2010/11. Around 95% of dwelling fire fatalities and injuries occur in “dwellings – single occupancy”.

The majority of accidental dwelling fire incidents start in the kitchen. Figure 32 shows the distribution: kitchen, 54%, living/dining room, 12%, bedroom/bedsit, 10%. As upholstered furniture predominates in living/dining rooms and bedroom/bedsits, it will only exert a significant influence on fire growth in fewer than a quarter of dwelling fire incidents.

Of the 1 800 fatalities in accidental dwelling fire (excluding those at Grenfell Tower) occurring between 2010-11 and 2019-20, the majority (almost 1 600) occurred either in kitchens (16%), bedrooms or bedsit rooms (30%), or living/dining rooms (42%), as shown in Figure 33. This shows that fires in rooms with the most upholstered furniture are much more likely to involve a fatality than those occurring elsewhere, although the activities in these rooms, such as relaxing and sleeping, are also likely to contribute to a higher proportion of fire deaths.

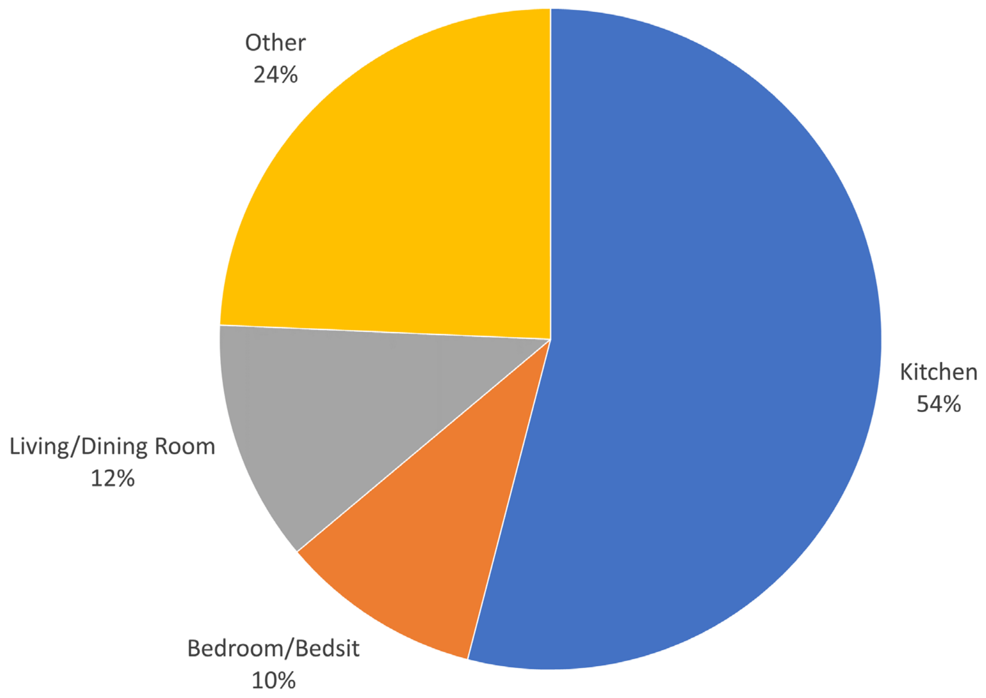


Figure 32 Location of start of accidental dwelling fires, England, combined data 2010/11 to 2019/20

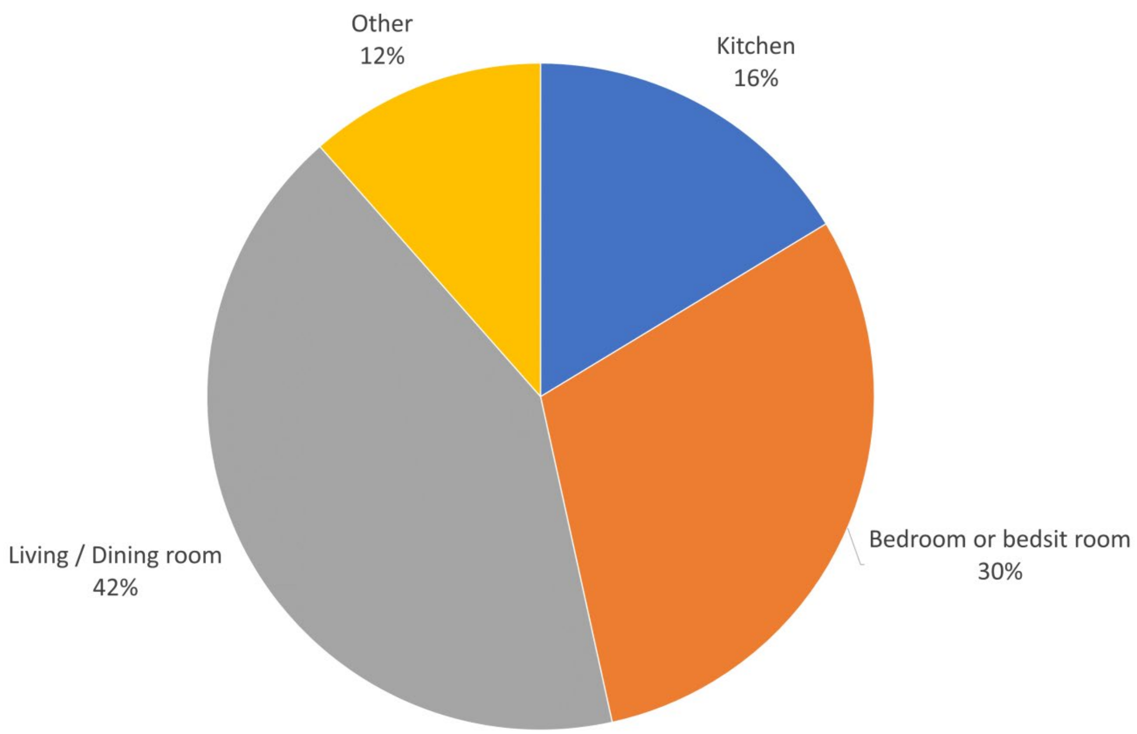


Figure 33 Fatalities in accidental dwelling fires, by location of fire start 2010/11 to 2019/20

Figure 28 showed that for the period 2010 to 2020, 77% of fire fatalities occurred in dwellings. These have been broken down by location within the dwelling in Table 21. Although only 22% of fires occur in bedrooms, living rooms and dining rooms, these account for 72% of the fatalities, with about 20 fatalities per 1000 fires. Since most upholstered furniture is located in these rooms, this suggests that fires involving upholstered furniture may be disproportionately more dangerous than other domestic fires, both because of the type of activity in these rooms, and because of the large mass of ignitable material. This allows the role of upholstered furniture in fire fatalities to be estimated (although in fatal fires, which are usually fully developed, reliable identification of the material or item first ignited is often impossible).

Table 21 Proportion of accidental dwelling fires, fire fatalities and fatalities per 1000 fires by location of fire start for England from 2010-2020

Location within dwelling	No. of fires %	Fatalities %	Fatalities per 1000 fires
Kitchen	54	16	1.9
Living/Dining room	12	42	22.9
Bedroom/Bedsit	10	30	19.6
Other	24	12	3.3

A1.2.5 Fires by material or item first ignited

In order to estimate the impact of upholstered furniture and flame retardants, and any specific items of upholstered furniture, on the risk of serious fire, the fire statistics reported for England over the period 2010 to 2020 identifying the *material or item first ignited* have been analysed. The data are all presented as averages per year over the 10-year period. There is considerable statistical fluctuation within the data, but no clear trends emerge over the last decade.

Of an average of 31 915 fires, 7 990 (or 25%) identify textiles, upholstery and furnishing as the material or item first ignited and so the categories examined here only represent around a quarter of the dwelling fires in England over this period. A slightly larger number of fires started with food burning (28%), and also structure and fittings (18%), paper/cardboard (6%) and various other materials or items igniting first.

Average data for the preceding 10 years are presented, alongside the percentage contribution to that category. Figure 34 shows the number of fires where the material or item first ignited was reported as textiles, upholstery, and furnishings.. The figure shows that clothing/textiles were most often the material or item first ignited (38%) followed by foam, rubber and plastic (33%). The furniture and furnishings group has been subdivided into individual categories, and shows roughly equal contributions from bed/mattress and upholstered furniture, of around 6% (or 1.5% of total) dwelling fires.

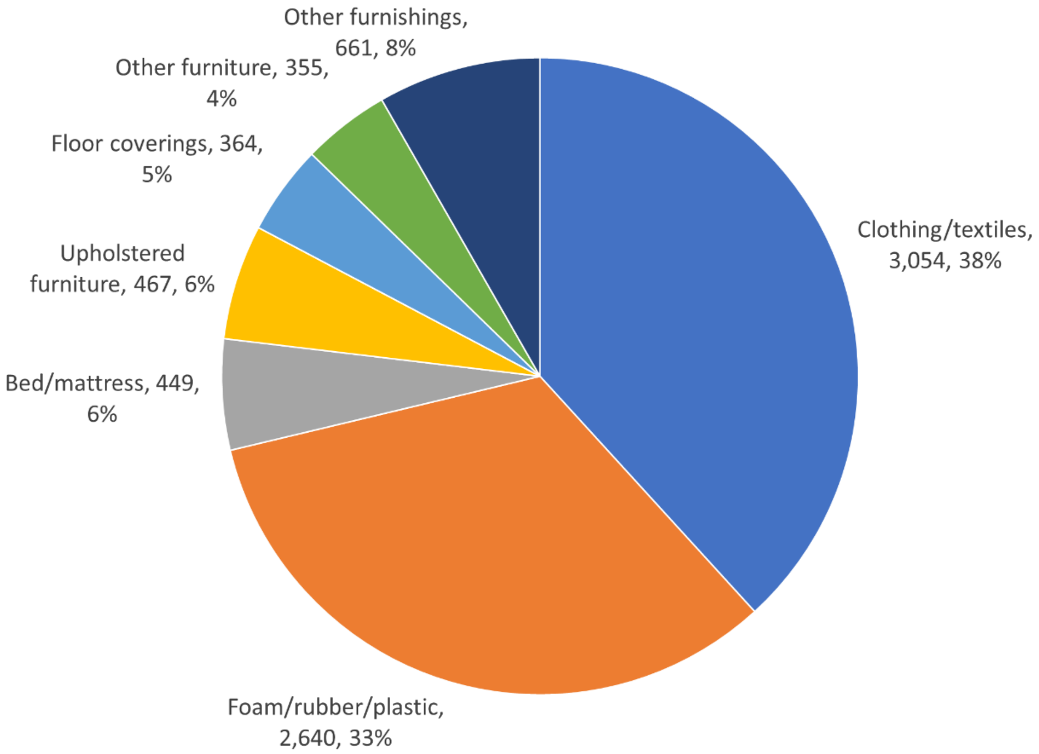


Figure 34 Breakdown of total number of dwelling fires from 2010 to 2020, by material or item first ignited. .

Figure 35 shows the average number of fatalities by material or item first ignited for textiles, upholstery, and furnishings. From an average of 222 dwelling fire fatalities per year, 115 (or 52%) resulted from textile, upholstery, and furnishings being the item first ignited. Figure 35 shows that the majority of these fatalities resulted from clothing/textiles being the item first ignited (56%), followed by upholstered furniture, 18%, (or around 9% of the total), and bed/mattress 11%, (or 6% of the total).

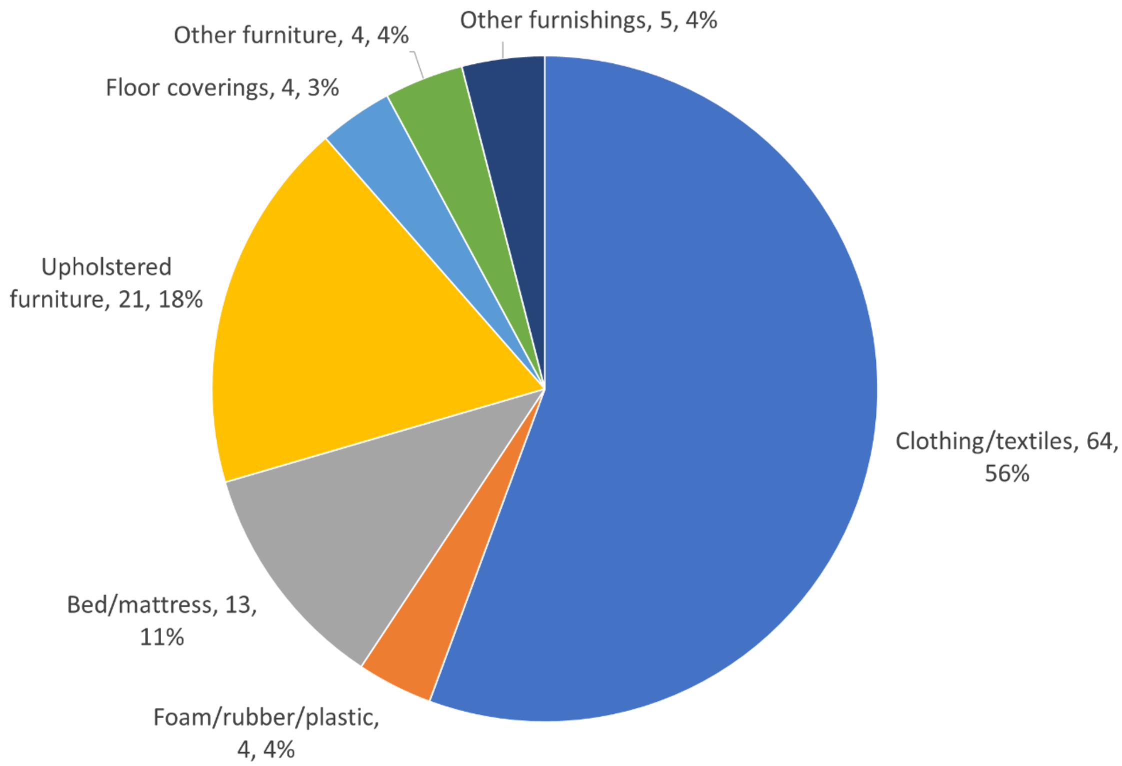


Figure 35 Breakdown of dwelling fire fatalities from 2010 to 2020 by material or item first ignited.

Figure 36 shows the average number of non-fatal casualties by item first ignited for textiles, upholstery, and furnishings. From an average of 6 055 dwelling fire non-fatal casualties per year, 1 954 (or 32%) result from textiles, upholstery, and furnishings being the material or item first ignited. From the figure, it can be seen that clothing/textiles contribute 45%, followed by foam, rubber and plastic at 20%. Bed/mattress and upholstered furniture each contributed around 8% (or 2.6% of the total) non-fatal dwelling fire casualties.

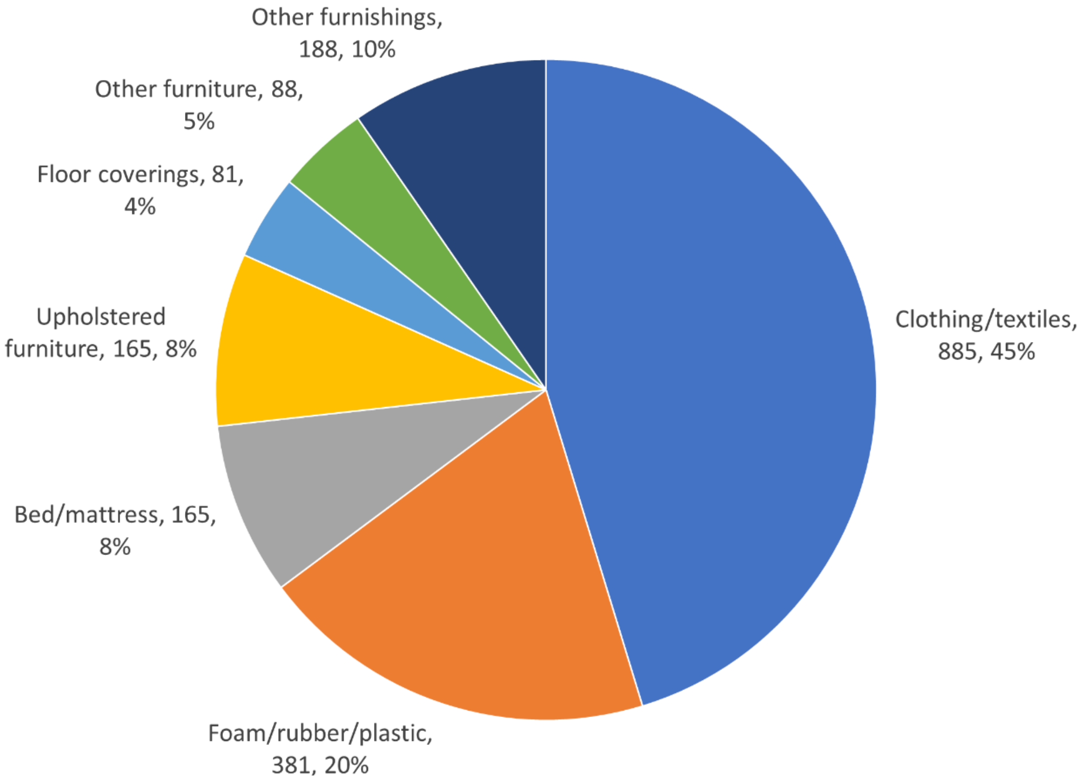


Figure 36 Breakdown of total number of non-fatal casualties in dwelling fires from 2010 to 2020 by material or item first ignited.

Thus, in terms of material or item first ignited, fires involving upholstered furniture and bed/mattress are factors of 3 and 1.8 more likely to be fatal, respectively, than fires starting with clothing/textiles, foam/rubber/plastic, floor coverings, or other furniture, but this only represents a total of 29% of dwelling fire fatalities.

A1.2.6 Data on material mainly responsible for fire development

The fire statistics for England also report data identifying the *material mainly responsible for fire development.* These have also been analysed and presented as averages per year over the period 2010-20. Although there is significant statistical fluctuation within the data, a downward trend in both number of fires and number of non-fatal casualties is apparent, there is no similar trend in the fatal casualty data over the last decade.

Again, the categories represent around a quarter of the primary dwelling fires in England over this period (other large categories were food 20%, paper/cardboard 5%, structure and fittings 15%). Figure 37 shows the number of fires where the material mainly responsible for fire development was reported as textiles, upholstery, and furnishings. Of an average of 31 915 fires, 8 021 (or 25%) identify textiles, upholstery and furnishing as the material mainly responsible for fire development. The figure shows that clothing/textiles were most often the material mainly responsible for fire development (35%) followed by foam, rubber and plastic (30%). The furniture and furnishings group shows roughly equal contributions from bed/mattress and upholstered furniture, of around 8% (or 2% of total) dwelling fires.

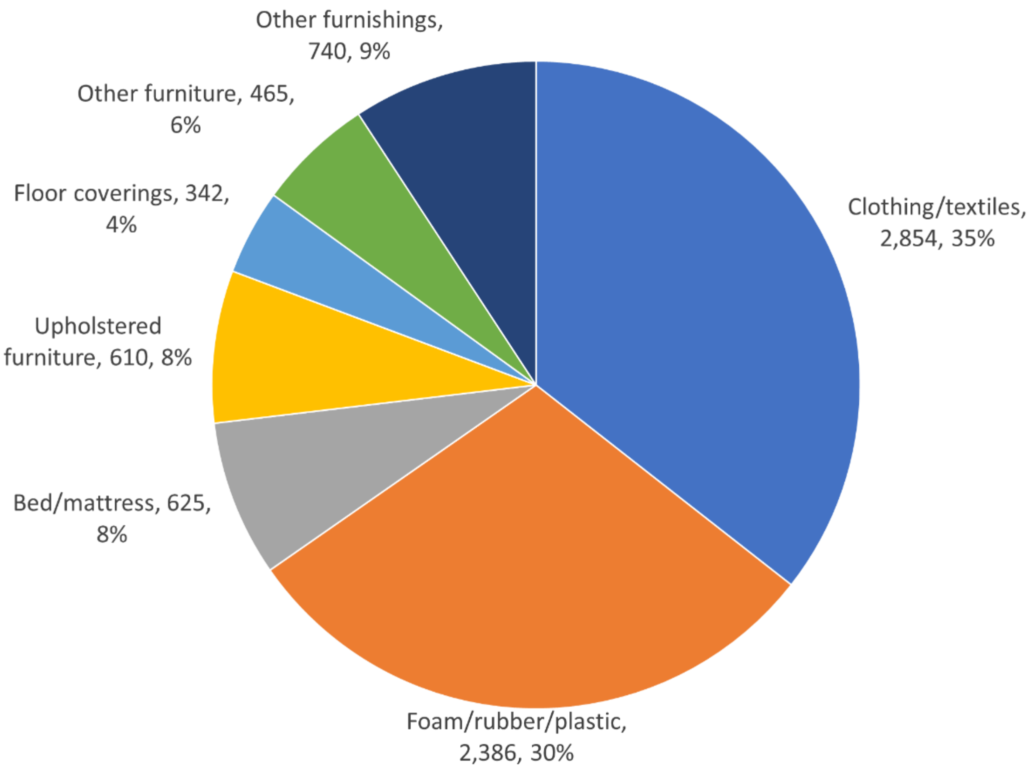


Figure 37 Breakdown of the total number of dwelling fires from 2010 to 2020, by material mainly responsible for fire development.

Figure 38 shows the average number of fatalities by material mainly responsible for fire development for textiles, upholstery and furnishings. From an average of 222 dwelling fire fatalities per year, 133 (or 60%) resulted from textile, upholstery, and furnishings being the material mainly responsible for fire development. Figure 38 shows that more of these fatalities resulted from clothing/textiles being the material mainly responsible for fire development (37%), followed by upholstered furniture, 25%, (or around 15% of the total), and bed/mattress 18%, (or 11% of the total).

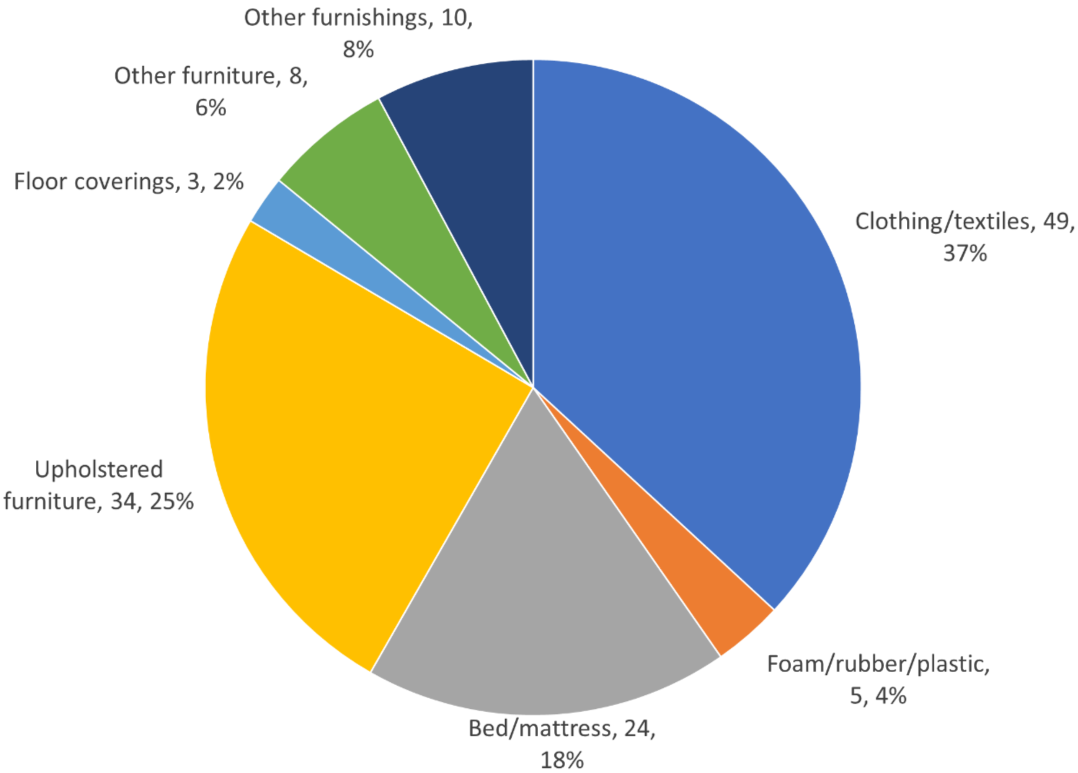


Figure 38 Breakdown of the number of dwelling fire fatalities from 2010 to 2020 by material mainly responsible for fire development.

Figure *39* shows the average number of non-fatal casualties by material mainly responsible for fire development for textiles, upholstery, and furnishings. From an average of 6 055 dwelling fire non-fatal casualties per year, 2174 (or 36%) result from textiles, upholstery, and furnishings being the material mainly responsible for fire development. From the figure, it can be seen that clothing/textiles contribute 38%, followed by foam, rubber and plastic at 17%. Bed/mattress and upholstered furniture each contributed 11 and 12% respectively (or 4% of the total) non-fatal dwelling fire casualties.

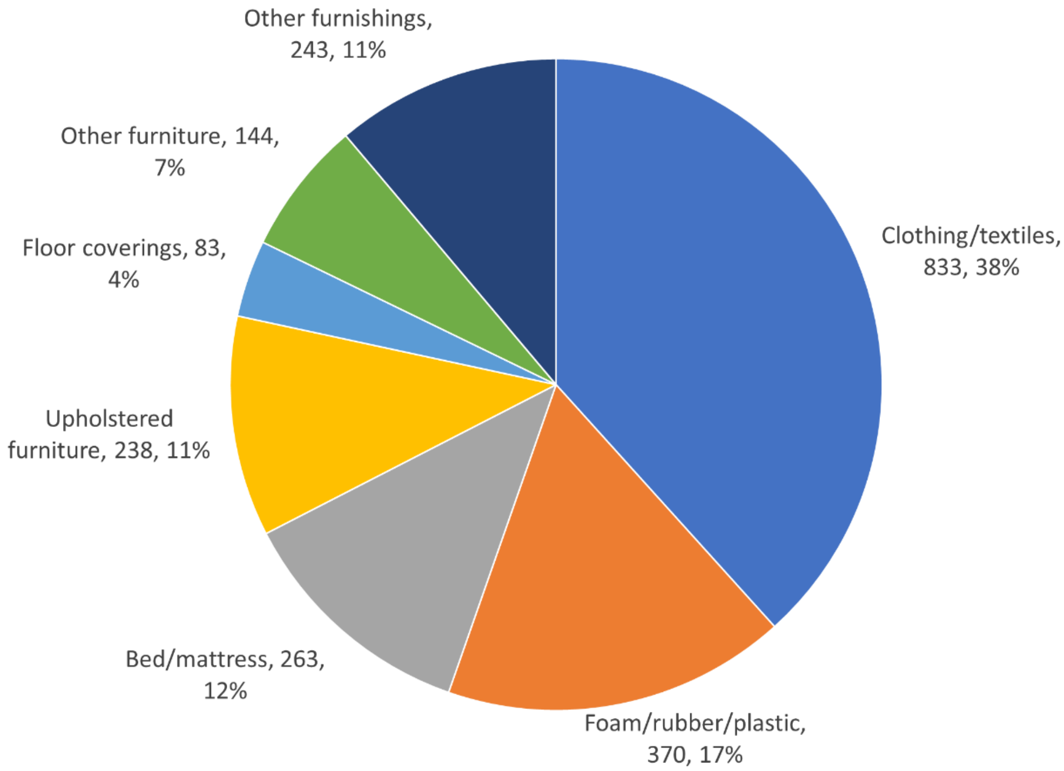


Figure 39 *Breakdown of the total number of non-fatal casualties in dwelling fires from 2010 to 2020 by material mainly responsible for fire development.*

In terms of material mainly responsible for fire development, fires involving upholstered furniture and bed/mattress are factors of 3.1 and 2.3 more likely to be fatal, respectively, than fires involving clothing/textiles, foam/rubber/plastic, floor coverings, or other furniture, which represents 43% of dwelling fire fatalities.

It is clear from a comparison of the *material or item first ignited* and the *material mainly responsible for fire development* data that the upholstered furniture and bed/mattress categories make a greater contribution to the material mainly responsible for fire development, than to the first item ignited data. This is understandable, since these items usually represent the largest fuel sources in most domestic settings. However, it is important to note that the chemical flame retardants used in England aim to suppress ignition in regulatory tests, and are not assessed for their influence on subsequent fire growth.

A1.2.7 Additional detail on Greater Manchester FRS Incident data

Individual FRSs frequently record further detail on their local systems in addition to the IRS data to meet the goals of their mission statements and performance indicators. This adds circumstantial information to the specific fields listed in the IRS. Discussion with data analysts from Greater Manchester Fire and Rescue Service (GMFRS) provide further insight into the IRS data. The free text box (10.4) in the narrative logs of the IRS data was searched for the keywords pillow, mattress, headboard, footboard, cushion, car seat, cot, highchair, and furnish*, in an attempt to match such entries against fatal fires and those with serious injury. This was a free text search of the additional information box with the results then filtered manually for relevance. As these results are not drawn from systematically categorised incidents, the quality and extent of the information provided is variable and its accuracy or completeness cannot be guaranteed. However, there was no evidence that any of these items were reported to contribute significantly to fire fatalities or serious injury. It was noted that many victims were reported as being trapped in some way.

Accidental fatal fires in residential premises, attended by GMFRS over the period 2009/10 to 2020/21 were considered alongside additional data from their fire investigator's team, coroner's reports and data analysis. (The data were provided covering this slightly longer period, but given the smaller number of deaths in this area, it was considered better not to remove the 2009/10 and 2020/21 fatalities from the data set.) Of 109 deaths resulting from 99 incidents, the cause was reported as "careless use or disposal of smoker's materials" in 57% of fatalities, followed by contact with flame/radiant heat in 17% of fatalities, with the remainder being divided between cooking equipment, faulty electrical equipment and others, as shown in Figure 40. Of the *contact with flame/radiant heat*, 12% of the fatalities were caused by space heating appliances, 4% by cooking appliances, and 1% other heat sources.

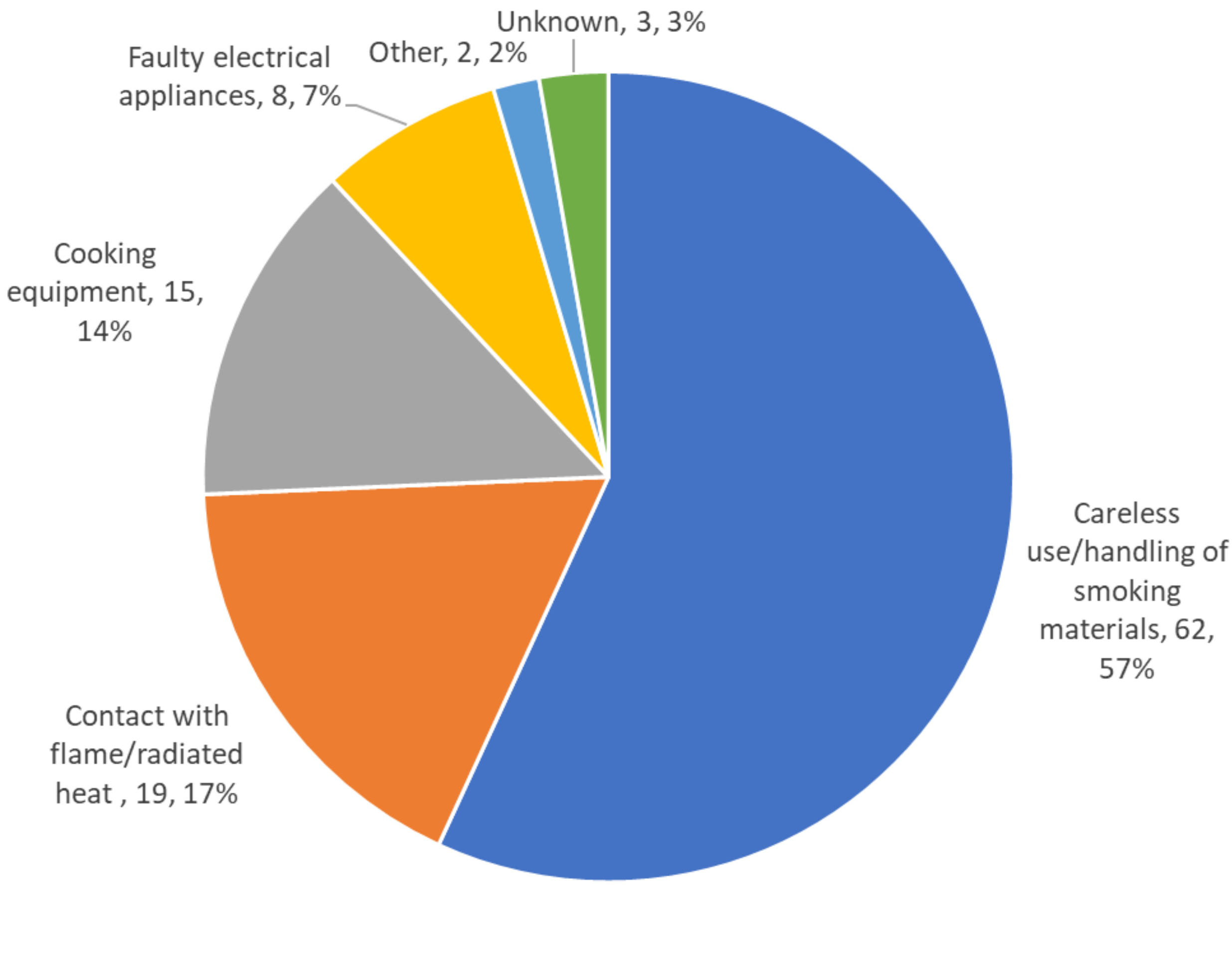


Figure 40 Cause of fire for accidental dwelling fire fatalities combined data from 2009/10 to 2019/20 attended by GMFRS.

The data also show the material or item first ignited as listed on the IRS but with supplementary commentary describing information from the fire investigators and coroner's reports. Where the commentary differs from the IRS category, the information from the commentary has been used. For example, when the material or item first ignited was listed as "other/unspecified furnishings", but the analysts recorded "cigarette, bedding", this was listed with "bedding" as the material or item first ignited. The GMFRS data are shown for comparison with the national data (Figure 35) so a comparison of their representativeness can be made. Figure 41 shows the material or item first ignited in these fatalities, which includes upholstered furniture 21% (in England it was only 9%), bed/mattress 7% (in England

6%) and bedding and clothing 31% (29% in England). Of the deaths, 17% were attributed to sofas, 4% to armchairs, and 1% to an unspecified item of upholstered furniture.

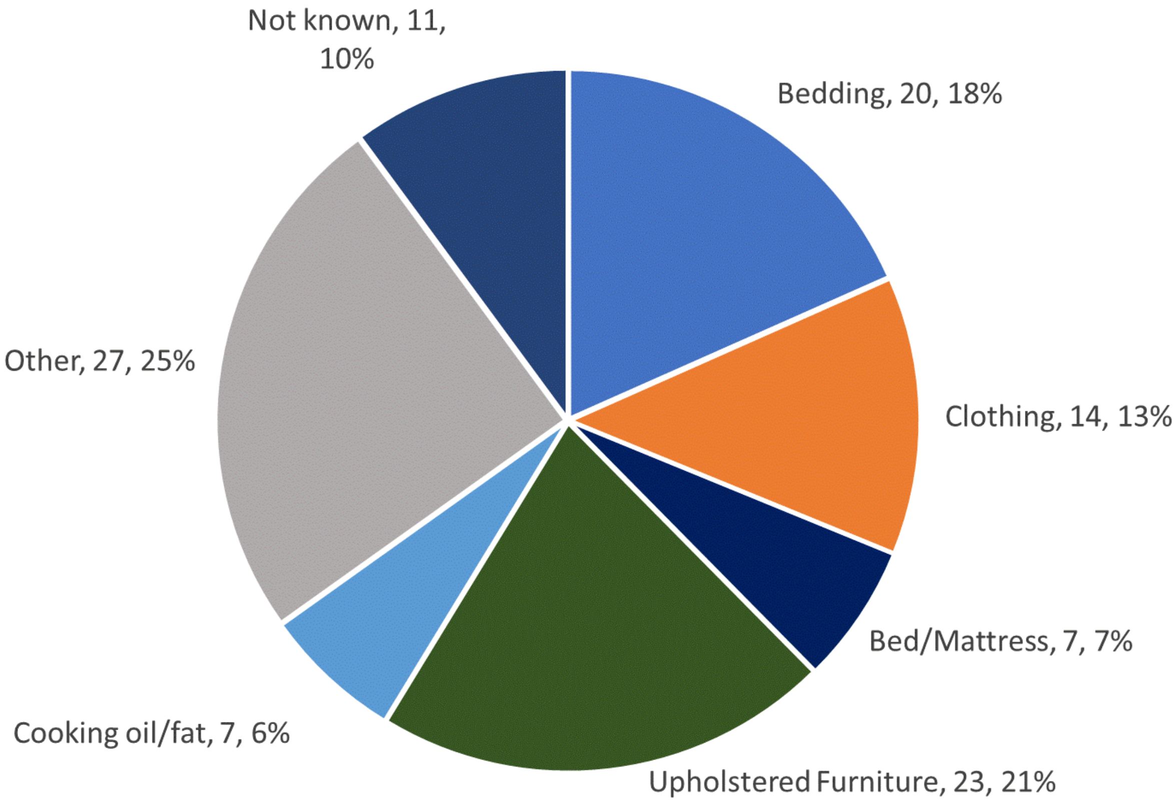


Figure 41 Material or item first ignited for accidental dwelling fire fatalities from 2009/10 to 2020/21 in fire attended by GMFRS.

The same approach was taken towards the material mainly responsible for fire development which is shown in Figure 42. Again, upholstered furniture contributed to 21% of fatalities, of which sofas (16%) and armchairs (2%) predominated. 17% of the fatalities list upholstered furniture as both the "material or item first ignited" and "material mainly responsible for fire development". Other furniture and furniture items were also shown, which showed a further 2% of fatalities involved sofas, 1% a fridge freezer and another 1% a toaster, with the causes being careless disposal of smokers' materials and faulty electrical equipment.

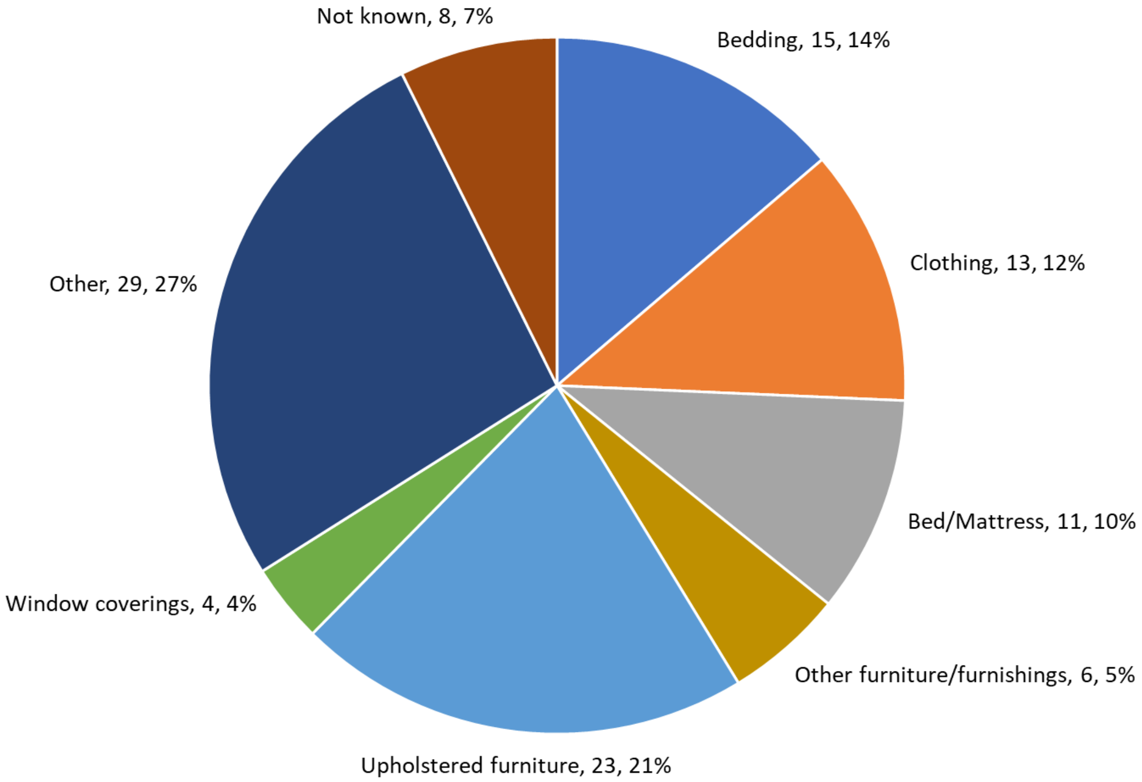


Figure 42 Material mainly responsible for fire development for accidental dwelling fire fatalities from 2009/10 to 2019/20 in GMFRS region.

In discussion, GMFRS' data analysts said they thought that fire deaths are more attributable to the person, their circumstances, health, living conditions, behaviour etc, than to specific furniture items or products. This highlights the difficulty of assigning fire risks to particular upholstered furniture product types. They also mentioned that, on returning from a fatal fire or other major incident, completing the IRS data was not always the lead firefighter's highest priority.

9. Annex 2 Description of Fire Retardants and their effects on smoke toxicity

A2.1 Fire retardant classification

Fire retardants have been classified in many ways:

- place of action – gas or condensed phase;
- mode of action – physical or chemical;
- chemical nature of agent – halogen, phosphorus, metal hydroxide or carbonate, etc.;
- means of incorporation of agent – additive or reactive (i.e. free to migrate, or chemically bonded onto the polymer chain – see section 3.3.2)
- Small molecule, oligomeric, or polymeric.

Unfortunately, many of these classifications cannot be unambiguously applied to particular fire retardants – for example, the most widely used fire retardant, aluminium hydroxide (Figure 3) releases water vapour, so acting in the gas phase, but in doing so absorbs heat and leaves a protective residue in the condensed phase[81]. Figure 43 illustrates one way the major fire retardant strategies could be subdivided[82]. It is worth noting that the flame inhibitors, or *flame retardants*, occupy a small portion of the total approaches.

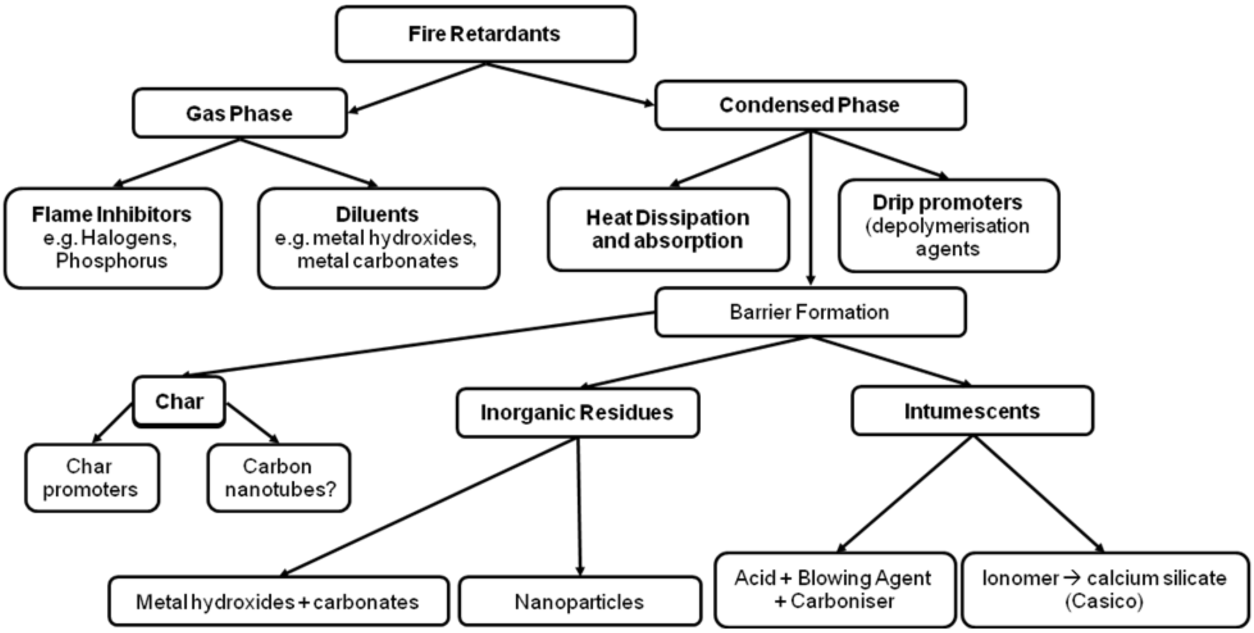


Figure 43 Classification of fire retardant strategies

A2.2 Major Fire Retardant Classes

A2.2.1 Halogenated and other gas phase flame retardants

Halogenated flame retardants act by releasing hydrogen halides (chlorides or bromides) (HX) during thermal decomposition. If the hydrogen halide release coincides with fuel gasification, then HX can interfere with the gas phase combustion processes. Comparison of the energy (or temperature at which the polymer has acquired such energy) of decomposition of HX with, for example, decomposition of C-C bonds indicates which type of halogenated flame retardant is likely to be most suitable for the structural unit of a particular polymer.

Table 1 shows the average bond energies of carbon-hydrogen and carbon-carbon bonds, compared with the rather weak C–I bond, increasing progressively to the very high strength C-F bond. Since their mode of action is dependent on scission of the C-X bond, fluorine- and iodine-based flame retardants are not used in practice because neither type is released into the combustion zone at the right moment. Fluorine cannot be effective as a radical interceptor in the gas phase because of its strong bond to carbon, whereas iodine is attached to carbon so weakly that it is liberated at polymer processing temperatures, and before polymer pyrolysis occurs[82].

Table 22. Bond energies and decomposition temperatures for polymer and carbon-halogen bonds (C is aliphatic carbon, C_{ar} is aromatic carbon)[83]

Bond	Bond Energy (kJ mol^{-1})	Onset of Degradation (°C)
Polymer bonds		
C—C	330-370	400
C—H	390-436	>500
C_{ar}—H	469	>500
C_{ar}—C_{ar}	518	>500
C==C	612	>500
Halogenated Flame Retardant Bonds		
C—I	222-235	180
C—Br	285-293	290
C_{ar}—Br	335	360
C—Cl	339-352	370-380
C_{ar}—Cl	419	>500
C—F	443-450	>500

Halogen atoms can be bound to aliphatic or aromatic carbon atoms in flame retardants. Aliphatic bromine compounds are easier to break down than their aromatic counterparts, and are more suitable for polymers with low decomposition temperatures.

Flaming combustion involves a very small number of highly reactive free radicals to propagate the gas phase oxidation processes. For ignition to occur, the number of radicals must exceed a critical threshold. Some reactions increase the number of free radicals. This occurs in reaction 1 and 2 where one free radical leads to three overall. Each "·" represents an unpaired electron.

$$H\cdot + O_2 \rightarrow OH\cdot + \cdot O\cdot \qquad (1)$$
$$\cdot O\cdot + H_2 \rightarrow OH\cdot + H\cdot \qquad (2)$$

Halogen-containing flame retardants act by interfering with the radical chain mechanism taking place in the gas phase. The high-energy OH· and H· radicals formed by reactions 1 and 2 are removed by the halogen-containing flame retardant.

At first the flame retardant breaks down to

$$RX \rightarrow R\cdot + X\cdot \qquad (3)$$

where X· is either Cl· or Br·.

The halogen radical reacts to form the hydrogen halide:

$$X\cdot + RH \rightarrow R\cdot + HX \qquad (4)$$

which in turn interferes with the radical chain mechanism:

$$HX + H\cdot \rightarrow H_2 + X\cdot \qquad (5)$$

The removal of the highly reactive H· is key to elimination of the main chain branching step, reaction 1, (stopping 1 unpaired electron becoming 3). HX also reacts with OH· radicals, removing another highly reactive radical from the flame:

$HX + OH\cdot \rightarrow H_2O + X\cdot$ (6)

The removal of OH· blocks the main heat release step of hydrocarbon combustion, the conversion of CO to CO_2, by replacement with less reactive halogen free radicals (X·) in the gas phase[84]. The H· and OH· radicals are essential for many flame reactions and OH· is essential in the main heat release in reaction 7.

$CO + OH\cdot \rightarrow CO_2 + H\cdot$ (7)

Loss of H· and OH· will increase the yield of toxic carbon monoxide and other products of incomplete combustion (organics, including hydrogen cyanide (HCN), organoirritants and soot). The high-energy H· and OH· radicals are removed by reaction with HX and replaced with lower-energy X· radicals. The actual flame retardant effect is thus produced by HX.

Kinetic reaction schemes predict that HBr must be recycled around 7 times to account for the observed flame inhibition[85]. Thus the hydrogen bromide is regenerated by reaction with hydrocarbon:

$X\cdot + RH \rightarrow R\cdot + HX$ (8)

In the condensed phase, the resulting unsaturated polyenes, which result from loss of HX may act as char precursors, forming products with a tendency to cyclize and condense to yield carbonaceous products, which protect the condensed phase below the flame zone against attack by oxygen and radiant heat. In PVC, after loss of 60% mass as hydrogen chloride from the surface layers, which acts as a gas phase flame retardant, char formation is a significant fire retardant mechanism protecting the underlying polymer.

The halogen content in the polymer compound, and its chemical binding, will dictate the flame retardant behaviour. In the presence of antimony oxide (Sb_2O_3), the efficiency of halogenated flame retardants is improved, although antimony has no flame retardant effect on its own. This is believed to result from the formation of volatile SbX_3 and other species which are more effective halogen carriers than HX.

A2.2.2 Mode of action of mineral fillers fire retardants

Incorporation of any non-combustible filler will reduce the flammability of a polymer, by reducing the total amount of fuel, the rate of diffusion of oxygen into, and fuel from, the polymer bulk while increasing the heat capacity, thermal conductivity, reflectivity and emissivity. There may also be synergistic or antagonistic catalytic[86] or other surface effects associated with the filler, and effects on the polymer melt rheology[87]. In addition, certain inorganic materials decompose endothermically with the release of inert gases or vapour, enhancing the potential fire retardant effect. In order to be effective, the decomposition must occur in a narrow window above the polymer processing temperature, but at or below the polymer's decomposition temperature. In practice most of the suitable materials are group II or III carbonates or hydroxides. They have three fire retardant effects, in addition to those of the inert fillers described above[81].

1. Endothermic decomposition, absorbing heat and therefore keeping the surrounding polymer cooler.
2. Production of inert diluent gases. Flaming reactions require a critical concentration of free radicals to be self-sustaining. If this concentration falls sufficiently, for example by the release of water or carbon dioxide, flame extinction will occur.

3. Accumulation of an inert layer on the surface of the decomposing polymer, shielding it from incoming radiation, and acting as a barrier to oxygen reaching the fuel, flammable pyrolysis products reaching the gas phase, and radiant heat reaching the polymer.

For example, aluminium hydroxide ($Al(OH)_3$), (which when used as a fire retardant, is commonly referred to as alumina trihydrate (ATH) and formulated as $Al_2O_3.3H_2O$, even though it is neither an alumina, nor a hydrate[88]), decomposes to form alumina (Al_2O_3) with the release of water. It breaks down endothermically forming water vapour, diluting the radicals in the flame, while the residue of alumina builds up to form a protective layer.

$$2\,Al(OH)_3\,(s) \xrightarrow{180\text{-}200°C} Al_2O_3(s) + 3\,H_2O(g)$$

$$\Delta H = +1.3\ kJ\ g^{-1}$$

It is worth noting that the heat capacity of organic polymers[89] vary from 0.9 to 2.1 J $K^{-1}g^{-1}$, thus the decomposition enthalpy of a fire retardant mineral filler is a factor of 1000 larger per gram than the polymer. The decomposition enthalpy of 1 g $Al(OH)_3$ is equal to the heat (q) required to raise the temperature of a mass (m) of 1.5 g of low density polyethylene (LDPE) from ambient temperature to decomposition (400°C). [$\Delta\theta$, assuming constant heat capacity (c) during heating, ($q = m\,c\,\Delta\theta$, so q = 1.5 x 2.3 x 375 = 1.29 kJ)]. Other mineral fillers include naturally-occurring brucite[90] (magnesium hydroxide) and huntite/hydromagnesite mixtures[91, 92].

A2.2.3 Mode of action of expandable graphite

Expandable graphite (EG) is a relatively new and potentially low toxicity fire retardant, which has been used to protect furniture fabrics and foams. Graphite flakes (typically 0.5 mm wide and 1 to 10 μm thick) are treated with sulphuric acid, which becomes intercalated between the individual graphene layers of the flake. On heating, the acid treatment volatilises, but cannot escape, significantly increasing the distance between the graphene plates. During a fire test, these pieces of expandable graphite, are frequently described as graphite worms because of their rapid and surprising increase in length[93]. This process is illustrated schematically, but not to scale, in Figure 44.

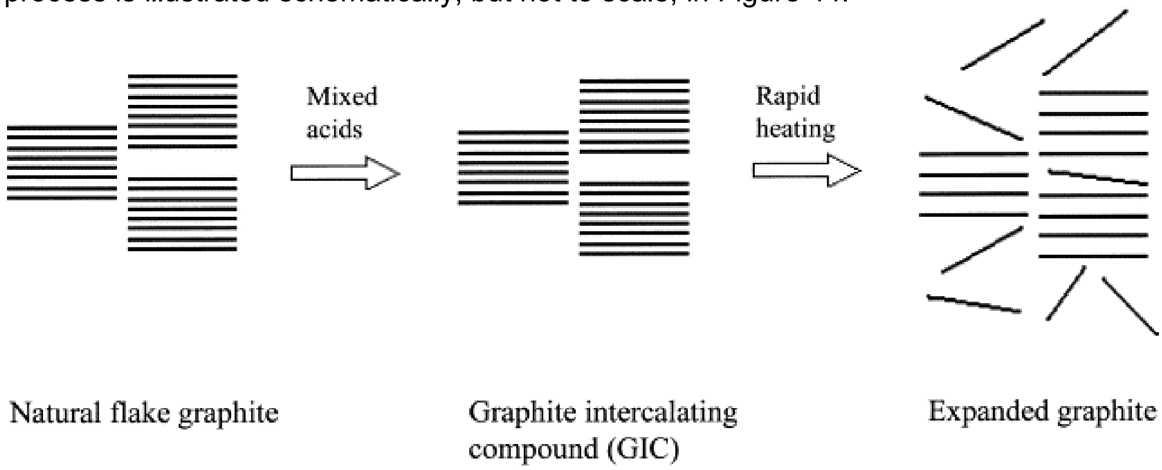


Figure 44 Schematic illustration of expandable graphite's fire protection mechanism (not drawn to scale)[93]

SEM images of char morphology in Figure 45 show the appearance of the worms deriving from the expansion of EG. It has been suggested that the expansion of EG is due to a redox process between sulphuric acid (H_2SO_4) and the graphite that originates the blowing gases[94] according to the reaction:

$$C(s) + 2H_2SO_4\,(l) \rightarrow CO_2\,(g) + 2H_2O\,(g) + 2SO_2\,(g)$$

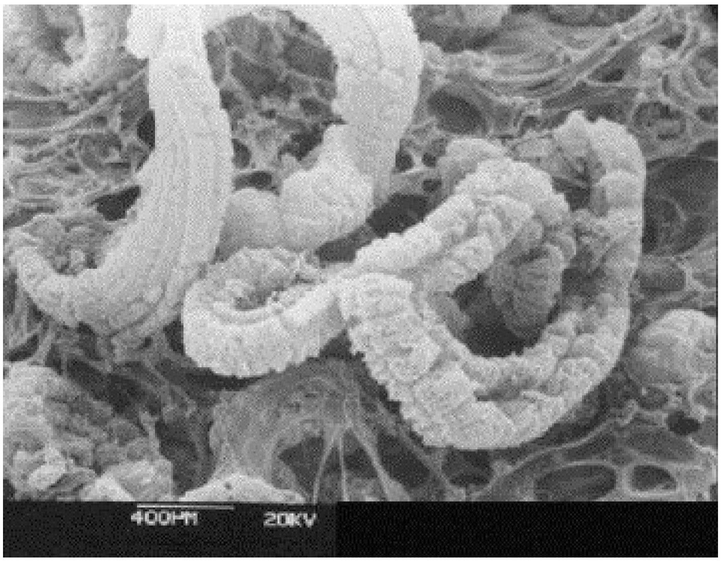


Figure 45 SEM of Char layer of expandable graphite filled foam showing "worms"[95] .

The blowing effect increases of the volume of the EG by about 100 times on heating above 200 °C. The "worm" like structure developed by graphite expansion forms a compact char layer which limits heat and mass transfer from polymer to the flame, preventing further decomposition of the material[95].

A2.2.4 Mode of action of melamine as a fire retardant in flexible polyurethane foam

Flexible polyurethane foam is widely used in upholstered furniture. It is made by reaction of toluene diisocyanate[96] with a polyol forming urethane and other linkages. On heating, the urethane linkages break, and the more volatile toluene diisocyanate is reformed. It will volatilise and fuel flaming combustion. As the decomposing foam gets hotter, the polyol also starts to breakdown and contributes further to the fuel load. Each melamine molecule has three amino (-NH_2) groups. Isocyanates react rapidly with amines forming large cross-linked, non-volatile structures anchoring the isocyanate in the condensed phase. The chemistry is illustrated in Figure 46[97].

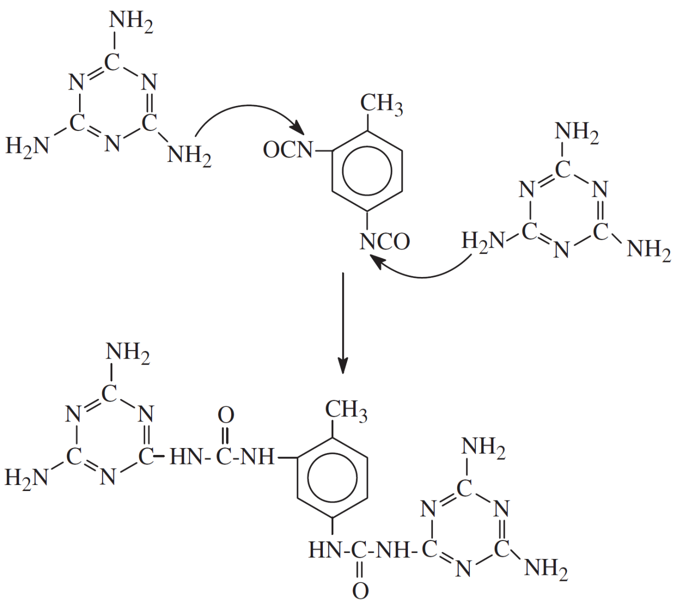


Figure 46 Reaction of two melamine molecules with a toluene diisocyanate molecule to form a non-volatile residue[97]. The availability of further amino groups to react with further isocyanates is evident in the figure.

A2.2.5 Layer-by-layer deposition of environmentally benign fire protective coatings

A novel technique which has been pioneered in various research institutes is layer-by-layer deposition (LbL). This has been demonstrated to protect both fabrics and foams. Highly effective fire protection, capable of meeting regulatory requirements, is easily achieved often resulting from only 5 or 10 molecular layers on the surface of the fabric or foam, and resulting in a weight gain of less than 1%, and no change to the physical properties. It is achieved by dipping the fabric or foam alternately in two solutions which leave positive or negative charges on the surface, coating the entire surface and attracting and ordering the subsequent layer. The type of coatings range enormously, but include biologically derived molecules such as sugars and alginates[98, 99]. Unfortunately, while this can easily be achieved in a laboratory, the additional number of processing stages have so far limited its commercial viability.

A2.3 Impact of CFRs on smoke toxicity

UK fire statistics show that most fire deaths and most fire injuries result from inhalation of toxic smoke, and that this proportion is increasing, although overall fire deaths are decreasing. Smoke toxicity this included as part of the discussion, but does not feature in the fire risk matrix as it falls outside the scope of the project. Fire statistics also show that most domestic fires start in kitchens, but the most lethal fires start in living rooms and bedrooms. The large amounts, and high fuel load, of upholstered furniture and bedding present in these rooms suggests that they may make a significant contribution to those deaths.

While halogen-based flame retardants are effective in reducing fire risk, i.e., the probability of occurrence of a fire, they show a high fire hazard, that is, the probability of producing toxic, corrosive, obscuring smokes[100], producing much higher yields of the main asphyxiants, carbon monoxide (CO) and hydrogen cyanide (HCN). Dense smoke, from whatever source, obscures escape routes and contaminates property. Halogen acids (HCl and HBr) are highly corrosive, damaging metallic, electrical and electronic equipment, and significantly increasing the costs of unwanted fires.

Toxic smoke from fires is of increasing concern to firefighters as an occupational health and safety issue[101]. Possibly the study most relevant to the current project is that from the Underwriters Laboratory in the US[102]. They assessed different items of furniture for release of CFRs during accelerated ageing and tested the flammability and toxic gas releases in large scale fire tests. This showed that significant quantities of triphenyl phosphate (TPhP) and tris-isobutylated triphenyl phosphate (TBPP) CFRs were released during accelerated ageing, and the same CFR was present in the smoke during the test. They also showed higher levels of toxic carbon monoxide and hydrogen cyanide from furniture relying on CFRs, rather than physical barrier fabrics.

10. List of Appendices

01 - **List of documents** included in the literature review for the concept mapping exercise

02 - **Guidelines** for annotators, a part of the concept mapping exercise

03 - **Concept network**, showing only the elements of the network that are part of the fire risk dimension of the furniture matrix

04 - **Concept network**, showing the fire risk elements of the network and how they relate to the furniture elements

05 - **Concept network**, showing only the elements of the network that are part of the FR exposure dimension of the furniture matrix

06 - **Concept network**, showing the complete set of FR exposure elements of the network

07 - **Concept network**, showing the FR exposure elements of the network and how they relate to the furniture elements

08 - **Concept network**, showing the complete integrated network, relating fire risk, FR exposure, and furniture elements

09 - **Code list**, showing all of the concepts that were included in the concept network, and how they are included in the matrix

10 - **Citation data** for the full set of studies retrieved from the broad Scopus search n=3385

11 - **Questionnaire** for evaluating fire risk in furniture, blank version

12 - **Questionnaire** for evaluating fire risk, including calculations for combustible volume

13 - **Questionnaire** for evaluating FR exposure from furniture, blank version

14 - **Questionnaire** for evaluating FR exposure from furniture, including calculations for surface area

15 - **Furniture matrix data analysis**, data visualisation, and raw data from the evaluation questionnaires

16 - Explanation by S. Harrad as to why there is insufficient data to directly measure contribution of furniture to human FR load

17 - **Dendrogram**, annotated and unannotated version, showing furniture product type clusters

18 - Furniture risk vs. exposure **matrix**

19 - **Sensitivity analysis**

20 - Market surveillance interview transcripts

21 - **Risk score** pseudocode

11. References

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