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Review

Meta-Narrative Review of Artificial Intelligence Applications in Fire Engineering with Special Focus on Heat Transfer through Building Elements

Iasonas Bakas * and Karolos J. Kontoleon

Laboratory of Building Construction & Building Physics, Department of Civil Engineering, Faculty of Engineering, Aristotle University of Thessaloniki, GR-54124 Thessaloniki, Greece; kontoleon@civil.auth.gr
* Correspondence: iasompak@civil.auth.gr

Abstract: Artificial intelligence (AI), as a research and analysis method, has recently been gaining ground in the ever-evolving scientific field of fire engineering in buildings. Despite the initial delay in utilising machine learning and neural networks due to the shortfall of available computational power, a review of cutting-edge scientific research demonstrates that scientists are now exploring and routinely incorporating such systems in their research processes. As such, a considerable volume of new research is being produced comprising applications of AI in fire engineering. These findings and research questions ought to be summarised, organised, and made accessible for further investigation and refinement. The present study aims to identify recent scientific publications relating to artificial intelligence applications in fire engineering, with particular focus on those tackling the issue of heat transfer through building elements. The method of the meta-narrative review, as implemented in the field of medical advancement research, is discussed, adapted, and finally utilised to weave a narrative that enables the reader to follow the most recent, influential, and impactful works. Efforts are made to uncover trends in the search for heat transfer models and properties under fire loading using AI. The review concludes with our thoughts on how future research can enrich the current findings on heat transfer in buildings exposed to fire actions and elevated temperatures.

Keywords: artificial intelligence; machine learning; neural networks; fire engineering; heat transfer; building; structure

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1. Introduction

1.1. Motivation for This Review

Along with sustainability, artificial intelligence (AI) has recently become one of the most prominent topics of discussion both in scientific and commercial circles. Numerous new studies have emerged utilizing AI and machine learning tools, attempting to introduce the power of mechanized cognitive processes into their research. Researchers in the fields of fire engineering and heat transfer, despite showing a small delay in adopting such tools and methodologies [1], are now aware of the benefits that AI can bring to their work and have started exploring such technologies [2].

The frequent release of new AI algorithm topologies, the multiple approaches of implementing existing AI models, and the constant development of more powerful supporting hardware require researchers and scholars to keep up with a technological scene which is evolving at a staggering pace [3]. Such an active and diverse environment necessitates regular reviews of the tools, applications, and solutions developed thus far to consolidate and solidify existing knowledge and to establish an informed direction for further research and exploratory studies. The present review study responds to this need by bringing together primary research in the fields of heat transfer and fire engineering, through the prism of artificial intelligence.

1.2. Scientific Context and Meta-Narrative Approach

Although it is beyond the scope of this work to provide a detailed description of each examined scientific field (fire engineering, artificial intelligence, and heat transfer), drawing a high-level outline is considered useful in terms of setting this review in context. All three fields are multifaceted and incorporate a wide array of interconnected disciplines, relevant to different scientific, commercial, and industrial applications.

Establishing an overall definition for fire engineering is difficult; however, considering that drafting fire strategies and carrying out risk assessments are a significant part of the field, it becomes apparent that, at a minimum, a solid understanding of building and infrastructure design is necessary. It is expected that computational methods, computer science, and even psychology could be added to the toolbox of a competent fire engineer, coupled with human and crowd management [4]. Knowledge of mechanical or structural engineering along with fluid dynamics, heat transfer, and material science could also be crucial to the operations of a fire engineer depending on their exact field of expertise [5]. Consequently, the scope of a fire engineer's work, either in an academic or industrial post, is vast.

Equally large is the extent of artificial intelligence itself. An overarching definition of AI is the ability of computers to emulate the human cognitive process [6]. However, it is particularly challenging to delve into specific algorithm architectures, model training strategies, and applications without first narrowing down the scope of this review considerably. Figure 1 is an attempt to briefly list the most frequently used algorithm structures organised in groups depending on their training needs. The reader is encouraged to refer to the AI and machine learning literature for details relating to each of these categories and algorithm topologies [7]. Although the specific benefits of using AI are explained more thoroughly as part of the following review, it is important to consider the various disadvantages or weaknesses of the currently available algorithms and methods. Some prominent considerations are given in the list below:

- For supervised or semi-supervised artificial intelligence models, a vast amount of training data are usually needed. The availability of such data is not always guaranteed.
- Even in cases in which the data are available, the formatting and preprocessing needed before the information is fed to an AI algorithm are often long and painstaking, potentially outweighing the time benefits of using such algorithms in the first place.
- Coding knowledge is necessary to enable the scientific team to not only be able to construct an AI algorithm, but also to make informed decisions in terms of its modification and adaptation to their specific field of research's needs. Specialist coding knowledge or having a good understanding of a coding language can be a barrier for some scientific teams.
- Interpretability is a weak point of the currently available AI models. Often a "black box" situation challenges a scientist's understanding of the validity of their model output. The development of explainable neural networks is attempting to tackle and mitigate this problem.

Although heat transfer is a much better-defined notion, it affects countless other physical processes and phenomena [8]. Trying to list all such connections is beyond the scope of the current review, which has to focus on the specific field of heat transfer in buildings to draw meaningful and targeted conclusions.

Considering the diversity of applications and breadth of the reviewed disciplines, an organised but non-rigid method of recording, comparing, and discussing overarching information is essential. Such flexibility can be achieved using the meta-narrative, semi-systematic review approach, which focuses on the essence of primary research findings and methodologies, without necessarily getting tangled up in the specifics of the amalgamation of statistical analyses and numerical results [9]. Before outlining the scientific method followed in this review, it is worth establishing its scope and highlighting the boundaries set to prevent over-generalised conclusions or an unnecessarily convoluted review process.

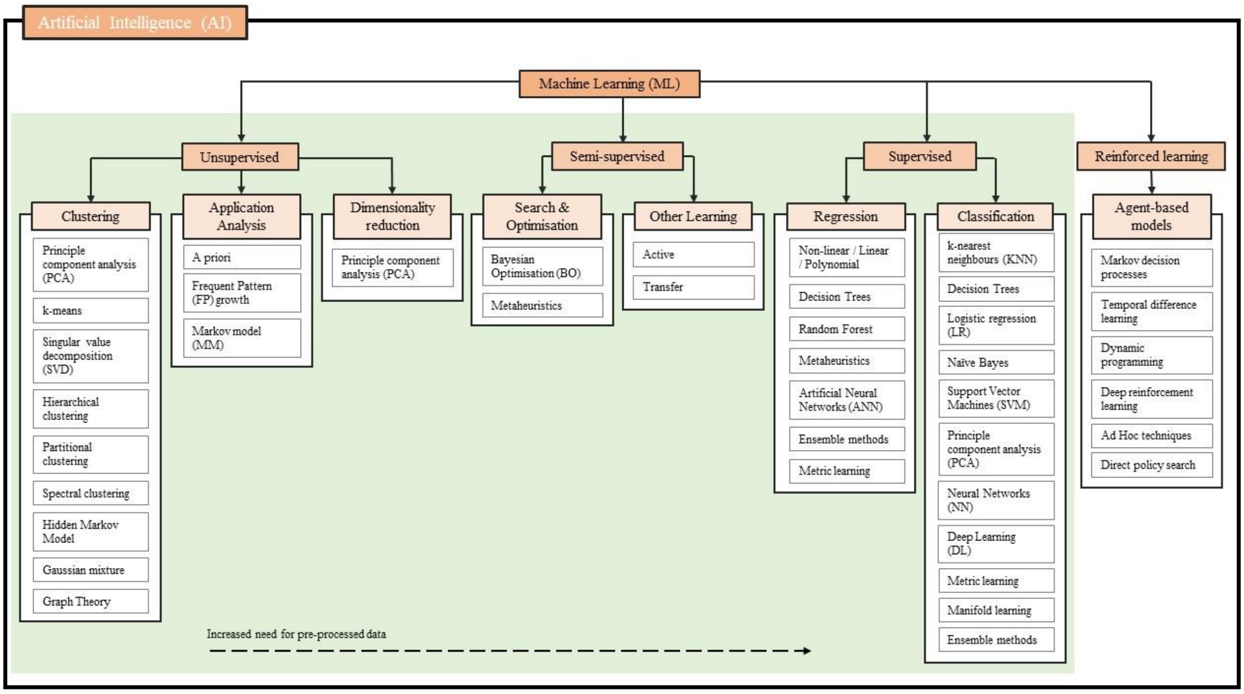


Figure 1. Organogram of most commonly used AI algorithms grouped by training method [1,10].

1.3. Scope and Limitations of the Present Review

Given the vast scope of fire engineering, heat transfer, and artificial intelligence, our criteria had to be limited to reduce the search space for this review. Primary and secondary research prior to 2000 was excluded from our consideration. Additionally, research written in languages other than English was not reviewed. Only scientific publications available on online indexing platforms were considered, while hard copies were not sought as part of this scientific effort. To ensure a minimum quality threshold, informal publications, university theses, and communications were excluded; only peer-reviewed research published in internationally recognised scientific journals was included.

Other than the technical considerations of language, publication year, and format, significant filtering was put in place to ensure that the reviewed articles aligned with the specific research interests of the review team. The heat transfer applications examined focused only on solid building elements exposed to fire or elevated temperatures. Particular attention was paid to walls constructed of inorganic materials, playing a structural or non-load-bearing role. Once the initial sourcing of primary research studies was complete, additional quality criteria were used as part of the review process. Details on these criteria are provided in the subsequent section of our research methodology.

1.4. Innovations and Contributions of This Study

Coordinated efforts to locate previously published works reviewing the current progress on use of artificial intelligence in the field of heat transfer due to fires in buildings had limited success. As such, the present study is considered to be the first major attempt to collate the information of primary scientific works in these specific fields, to review them critically, and to highlight the results, observations, and research questions of such studies. Consequently, one of the contributions of this meta-narrative review is to consolidate existing knowledge and to inform contemporary research efforts in the field of heat transfer due to fires in buildings. Its conclusions and references are aimed at directing future scientific efforts towards understanding and utilising the power of artificial intelligence in the aforementioned fields.

Another innovation of this study is that it moves away from a purely numerical meta-analysis review of the existing literature and instead develops a narrative, looking at issues, developments, and opportunities from a qualitative perspective. Although algorithms, specific numerical case studies, and statistical results are of great importance in terms of decision making and further expanding the scientific community's understanding, a concise narrative can be valuable in highlighting gaps and presenting the bigger picture of current research affairs in the field.

As part of the review process and in strict compliance with the set review protocol, some observations were made in relation to the clarity of several primary research papers' presentations of their methodology and reproducibility. Although further details are presented in the results and discussion sections later in this manuscript, bringing such issues to the attention of the research community is another contribution of this work.

In the same vein, using the alternative approach of a meta-narrative to review the existing literature requires a well-defined and transparent methodology. This study is innovative in that it establishes and follows a well-structured and clear review protocol. Existing research protocols developed in other fields are acknowledged, adjusted to our needs for AI, heat transfer, and fire research, and implemented to create a rich scientific text. The developed research protocol can be made available upon request, with the aim of enabling future meta-narrative review studies to be developed in a structured and transparent manner.

It is clear that making the best use of the advantageous nature of the meta-narrative review requires a well-constructed research protocol and structure for the process of recording, analysis, and narrative synthesis. The second section of this paper describes in detail the methodology followed to obtain relevant research articles, as well as assess and extract information before synthesizing the present narrative.

2. Review Methodology

2.1. Meta-Narrative Review Research Protocol and Change Control

Objectivity and transparency are paramount for the credibility of any research work; with that in mind, a strict protocol was established and followed for undertaking this review. Based on similar protocols drafted for the scientific field of distribution of medical innovations [11] and guideline studies focusing on the protocol of literature review itself [12,13], the methodology for this work was developed as follows:

1. Change control;
2. Research questions and guiding principles;
3. Scoping and search strategy;
4. Quality appraisal and data extraction;
5. Information analysis and narrative synthesis.

Despite the solid research protocol, the initial exploratory nature of the search necessitated adjustments. Such adaptations aimed to meet needs arising in the search process or to elucidate areas of interest identified following the completion of the initial protocol draft. Changes were recorded formally via numbered revisions; exploratory comments were logged in the dedicated Appendix of the protocol. Digital copies of every previous revision were retained and can be made available upon request. Major research protocol amendments were discussed and agreed upon with our research supervisor before being integrated into the methodology.

2.2. Research Questions and Guiding Principles

The aim of this review is not to contest or compare findings of previous primary studies in the field, but to present objectively the various applications of AI for the research of heat transfer in buildings exposed to elevated temperatures. The principle of "pragmatism" is followed throughout the review [14], ensuring that information is presented as found and avoiding subjective commentary in the Results section. The reader is encouraged to make their own assessment and valuation of such information. The principle of "peer review" is expected to harmoniously coexist with the pragmatic presentation of information in this review, ultimately creating a narrative that not only highlights existing examples of using AI in the field of heat transfer research, but also stimulates lateral thinking on further relevant applications.

This review is developed and built around three main research questions. These aim to explore and clarify not only the current relationship between AI, fire engineering, and heat transfer, but also to establish potential connections and research areas that are yet to be linked up with or progress based on cutting-edge artificial intelligence tools. The questions are outlined as follows:

1. What does the most recent (post 2010) research of heat transfer through masonry walls exposed to fires or elevated temperatures focus on?
2. What are the current scientific applications of AI in the field of heat transfer through masonry exposed to fire loading or elevated temperatures?
3. Are there examples of research on heat transfer in buildings using AI that could offer inspiration for similar methods to be used in the research of heat transfer through masonry walls exposed to fires?

2.3. Scoping and Search Strategy

A pilot application of the proposed methodology was used for scoping the proposed review field. A number of search terms were trialled on the indexing platforms listed in Table 1 to understand the extent and depth of the available primary research to date. The complete list of search terms and phrases used during the scoping phase is recorded in the Appendix of the original review protocol. The fundamental list of search key words is included in Table 2 below. Boolean operators and punctuation marks (and, or, +, "") were used to enhance and target the search process depending on the requirements and conventions of the various search engines. As part of the scoping exercise, a targeted preliminary search was conducted to identify existing review papers on or relating to the research questions listed above. The following scientific online publication platforms were used for identification of relevant research studies.

Table 1. List of online indexing platforms used along with the extent of reviewed results per search.

Online Indexing Platforms
IEEE Xplore (up to first 50 results)
Google Scholar (up to first 3 pages of results)
Science Direct (up to first 50 results)
Scopus (up to first 50 results)
Wiley Online Library (up to first 2 pages)
Springer (up to first 30 results)

Table 2. List of used search terms to obtain recent research on heat transfer through building elements exposed to fires with or without use of AI. Search terms organised according to the review aspect they relate to.

Artificial Intelligence	Heat Transfer	Building	Fire
Artificial intelligence (AI)	Heat transfer	Wall	Fire
Machine learning (ML)	Thermal response	Masonry	Elevated temperatures
Artificial neural networks (ANN)	Heat flux		
Deep learning (DL)	Transient heat		
Convolutional neural networks (CNN)			

For full list of the combined phrases used, please refer to the Review Protocol Appendix.

2.4. Quality Appraisal and Data Extraction

2.4.1. Initial Primary Research Filtering

Prior to any qualitative assessment of the studies being undertaken, technical criteria/filters such as language and date of publication were applied as outlined in Section 1.3: Scope and Limitations. The assessment of primary studies for inclusion or exclusion in the review process was undertaken in three stages. The initial assessment only considered the title and key words of the primary study, as appearing on the indexing online platforms. Depending on the degree of relation to the research questions set herein, the publications were added to the list for further review. Only in cases in which such relationship was ambiguous was the decision for inclusion or rejection informed by a brief review of the abstract. Once the initial stage of obtaining relevant studies was complete, a detailed review of the abstracts and methodology was undertaken. To avoid bias, the results section was not reviewed at this stage. Only the quality of the followed methodology and the degree of connection to the research questions of this review were assessed. To ensure transparency of the appraisal process, a 1–5 scoring system was used, in which 5 indicates a criterion is totally satisfied and 1 indicates a criterion is completely unsatisfied. Two distinct steps were undertaken as follows:

- Article titles, key words, and abstracts were reviewed first to confirm initial assessment of relevance to the research questions. Each article was scored from 1 to 5 depending on its relevance to the topic of the research area of this review. Articles scoring 1–2 were rejected and not assessed further. Articles scoring 3–5 at this stage were carried forward for further quality checks.
- Those considered relevant to the research topic were further assessed on the robustness of proposed method, the clarity and completeness of presentation of followed methodology, and the reproducibility of method (scoring 1–5 for each of these).

Studies with a mean of 3 or more (including relevance, robustness, clarity, and reproducibility) were carried forward to the final quality assessment stage which included a full review of their results, conclusions, discussion, and further research proposals.

At this stage, the technical contribution of each study towards answering the posed research questions was assessed before their final inclusion in the review narrative. The criteria used at this final stage, which included the clarity of presentation of results and discussion as well as the article's contribution to one or more of the research questions of this review, were counted towards the overall score of each individual study. Studies with an overall mean score of 3 or more were finally included in the present narrative.

2.4.2. Quality Assessment of Selected Articles

As a minimum quality threshold, only scientific studies published in peer-reviewed journals or conferences were considered. University theses and informal communications or publications were excluded from consideration.

Following the initial screening of articles, the research methodology and the quality of presentation were considered. Attention was paid to the protocols used for establishing artificial intelligence algorithms and the rigor with which their results were evaluated. The clarity and completeness of presentation of algorithm development methods were also assessed to ensure not only robustness of the process but also an algorithm's reproducibility as well as to avoid blind spots. The quality, breadth, depth, and meaning of the data used for training and evaluating the AI algorithms were another critical item assessed before the final inclusion of the study in the present review. Precision in the presentation of the results was also considered given that such information is fundamental for understanding the contribution of the reviewed study as well as for informing parts of this review's narrative.

For previously conducted literature review articles, the rigor and robustness of the followed review protocol were of paramount importance. The completeness of such protocols and their clarity of presentation were some of the criteria used to include/reject review papers. The sources and number of primary studies used for conducting said literature review were also used to assess the quality of the paper. Finally, the clarity of presenting the results and conclusions of the study was important to ensure that its contribution could be accurately transferred to the present review article.

2.4.3. Data Extraction Protocol

The extracted data aimed to provide answers to one or more of the scientific questions posed at the start of this document. The extracted data could be in the form of numerical values, statements, names of researchers and research institutions, titles of publications, and descriptions of AI algorithms or research techniques. The data were recorded on a dedicated "data extraction form". Each research question provided a headline and subsequently each primary study became an entry, providing part of the answer to a specific question. A primary study could be found under more than one research questions, if it provided useful information helping to answer different aspects of the proposed review. Upon completion of the review and data extraction process, a final review of the extraction forms was carried out to ensure there were no references or other information missing. The forms were reviewed for consistency of formatting and the details of the recorded information in preparation for the next stage of the review: data analysis and synthesis.

2.5. Information Analysis and Narrative Synthesis

The nature of the intended meta-narrative review shifts the focus of data analysis and synthesis from numerical meta-analysis to a qualitative assessment of the extracted data. The recorded answers to the research questions, as noted on the extracted data forms, were reviewed with the intention of highlighting patterns, gaps, or trends in current research and possible directions for new scientific investigations. The information providing direct answers to the scientific questions was presented and edited into a narrative, forming a foundation of current knowledge on the research field in question. Relevant studies and the data extracted therein were compared to each other with the aim of identifying gaps or clashes in relation to the specific scientific question investigated at the time. Based on the gaps identified, the prominent research trends, current direction of scientific investigations, and future lines of enquiry were considered while ideas on alternative/possible uses of AI in the research of heat transfer in buildings exposed to elevated temperatures were discussed with responses to the existing research being welcome.

The overall process of preparing the review protocol, executing the review, and finally synthesising the present narrative is illustrated in Figure 2 below. The diagram is schematic only and should be read in conjunction with the original review protocol or at least the preceding paragraphs of this study.

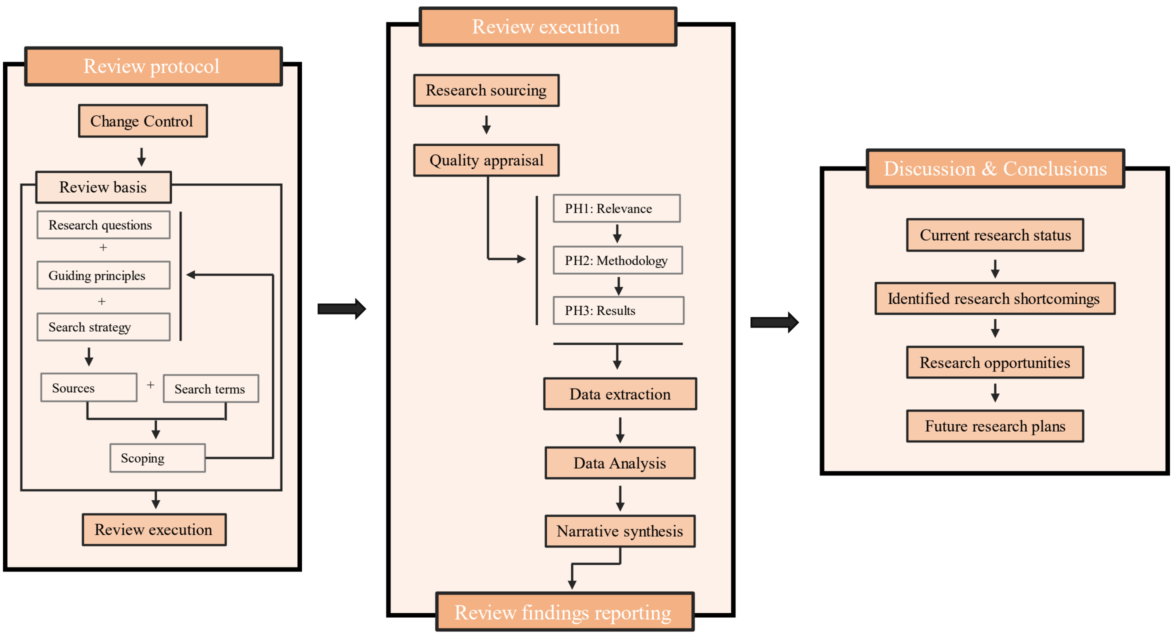


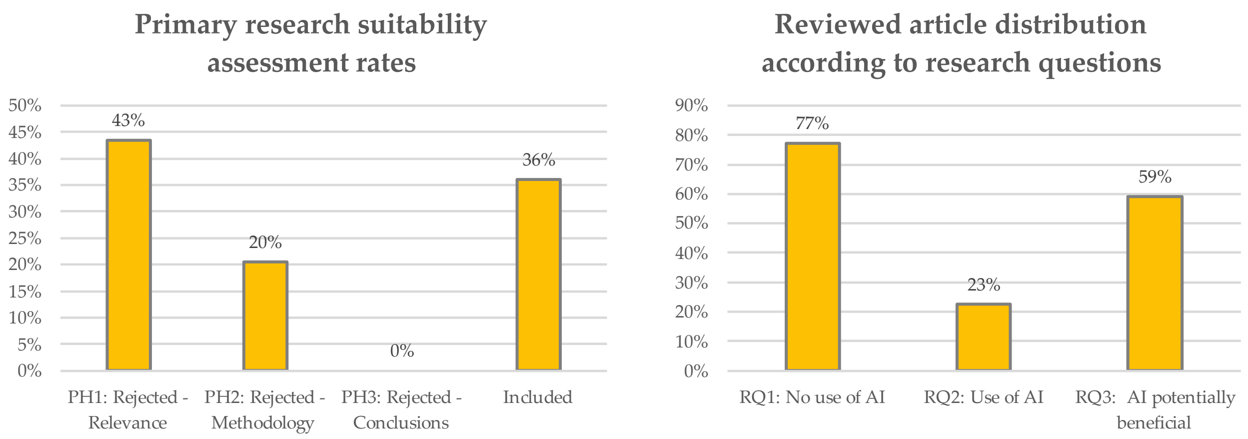
Figure 2. Flow chart of preparing and executing the present literature review article.

3. Results

3.1. Distribution and Features of Reviewed Articles

Before proceeding to the presentation of the technical and scientific information obtained through the literature review, it is worth establishing the wider context and trends observed through analysing, assessing, and categorizing the reviewed articles.

The initial search for relevant research work yielded a total of 122 articles. As described in the methodology section above, the search was only based on a review of their titles and key words. The subsequent filtering and assessment stages led to a significant reduction in and refinement of the research that was used as part of the present review. At the first stage of filtering, PH1, as shown in Figure 3a below, 43% of the obtained articles were rejected on the grounds of relevance to the research aims and interests of this work. A subsequent assessment of the remaining articles in terms of the quality and clarity of their methodology, presentation of results, and conclusions led to the rejection of an additional 20%. Finally, 36% of the originally obtained articles were used in the review (a total of 44 articles).

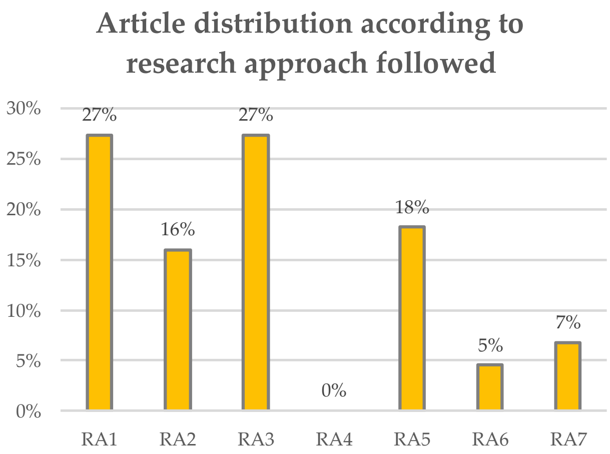


(**a**) (**b**)

Figure 3. Distribution of obtained and reviewed articles: (**a**) Primary research suitability assessment rates distributed in the three filtering phases described in the Methodology section; (**b**) Reviewed articles' distribution according to the three research questions on which this review has been developed.

The articles used for this review paper were then organised and distributed according to various criteria, aiming to reveal underlying trends in the currently available research. As seen in Figure 3b, 77% of the reviewed articles (34 articles) related to the first research question (RQ1) did not feature artificial intelligence as part of their method. Only 23% (10 articles) utilised or considered any form of AI as part of the applied methodology. Finally, 59% of the reviewed work could potentially benefit from the use of AI or could further enhance the methods already employed.

Delving deeper into the methods used in each study and recording their approach to using artificial intelligence, FE or statistical modelling, experiments, or any combination of these, some additional trends were revealed. As seen in Figure 4, 27% of the reviewed research papers (twelve articles) opted for a purely numerical or modelling approach. On the other hand, 16% (seven articles) only utilised information resulting from experimental work. A total of 27% of the articles was based on a combination of the two approaches, establishing a numerical model which was then validated using experimental data. No research studies relied entirely on artificial intelligence (i.e., no other investigation method was used in conjunction with AI to support, complement, enable, or help explain the results of such models), though a portion (18%—eight articles) supported their AI findings with numerical models or optimised their models using AI. A total of 5% of the reviewed research papers (two articles) founded their methodology on a combination of AI, numerical modelling, and experimental data, while 7% (three articles) followed the literature review path.



Ref	Research approach
RA1	Modelling and/or Numerical
RA2	Purely experimental
RA3	Modelling with Experimental validation
RA4	Purely AI
RA5	AI and Modelling
RA6	AI with Modelling and Experimental validation
RA7	Literature review

Figure 4. Reviewed article distribution according to the research approach followed.

Aiming to understand the reliance on experimental data, a further analysis was carried out on the research utilising such information. The distribution presented in Figure 5 shows that only 11% of the papers (two articles) relied on existing experiments while the vast majority (84%—sixteen articles) opted for carrying out new experiments tailored to the needs of their application. A small portion (5%—one article) used a combination of existing and new experimental data.

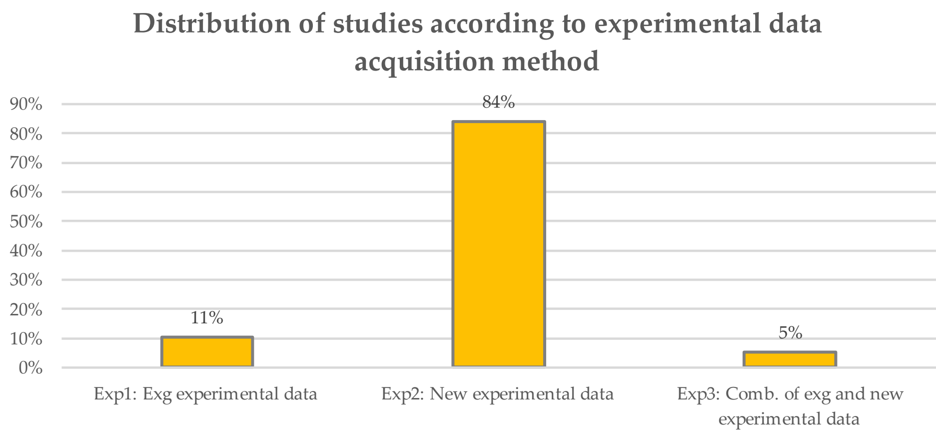


Figure 5. Distribution of studies according to experimental data acquisition method.

3.2. Research on Building Elements Heat Transfer Due to Fire

3.2.1. Combined Investigation of Thermal and Mechanical Performance of Walls

Particular focus has been put on the investigation of the combined effects of exposure to fire on the thermal and mechanical characteristics of masonry or concrete walls and cementitious mortars. Finite element analysis modelling was used to study the behaviour of masonry under elevated temperatures before validating the results with experimental data. Even though good agreement was observed, the lack of understanding of the boundary conditions and material properties was considered an obstacle in the modelling process [15]. A contributing factor to such a challenge was the lack of standardised and consistent documentation outlining the behaviour and material properties of masonry exposed to fire [16].

Despite such drawbacks, the significance of digital modelling was acknowledged, especially given the cost and complexity of full-scale destructive tests [17]. Establishing the necessary parameters for modelling (boundary conditions and material properties) can be made possible through experiments [18] and a subsequent calibration of numerical models. The alternative approach of a "temperature displacement coupled analysis model" was adopted to study masonry spalling, while reducing computational costs through the use of energy criteria [17]. Studying the mechanical degradation of bricks, spalling, deflection, and the heat distribution when exposed to fire is an integral part of the safe implementation of performance-based codes. Through this process, it was established that depending on the thickness of the wall, different failure criteria govern. Thinner walls fail structurally, while thicker ones tend to lose their insulating properties before complete mechanical failure occurs [18]. The material phase change due to elevated temperatures was considered in conjunction with all heat transfer mechanisms to understand the mechanical and thermal behaviour of clay brick walls, respectively. A finite element simulation was used to reverse analyse experimental results and to accurately establish modelling parameters based on physical observations. The effectiveness of such a model was ultimately demonstrated through a case study [19]. Adding to the complexity of the analysis, the impact of the way bedding mortar contacts bricks needs to be fully understood to mitigate the risk of modelling inaccuracies [20]. Aiming to overcome such a risk, the thermal and mechanical performance of hollow block walls was described using mathematical formulas developed to align as closely as possible to observed experimental results [21]. Similarly, it was established that simple heat transfer numerical formulas are adequate to predict thermal movement through samples made of conventional cementitious mixes [22].

When the masonry units under consideration are of a novel composition that has not been investigated before, the exact mix and properties need to be understood experimentally and used in conjunction with the above parameters to avoid modelling errors [23]. An example of such an investigation relates to the thermal and mechanical properties of concrete blocks with a percentage of aggregate and binder substitution with sludge ceramiste and GBBS, respectively. The study showed the dependency of their thermal and mechanical performance on the exact composition of each sample [24]. A similar in-depth understanding of material properties was necessary when investigating reinforced concrete walls. Although their mix appeared to not greatly affect their thermal performance during their exposure to fire, it did affect their residual mechanical properties post exposure [25].

The interface between the body of a wall and a fire source also affected the performance of the system. Basic mathematical models were developed to describe the thermal and mechanical behaviour of clay brick walls rendered with various plaster mixes against a fire source [26]. In the same vein, the impact of a steel plate formwork and other components was examined when a composite concrete and steel wall was exposed to fire. The initial FE model was benchmarked against experimental data from the published literature. It was highlighted that a standardised design process is needed for such elements to handle fire exposure [27]. A similar approach was followed for the study of concrete sandwich walling panels; an FE model was validated against published experimental data. A further step was made to demonstrate the proposed model on a case study, before concluding that contemporary reports relating to the fire performance of such units tend to overestimate their mechanical capacity [28].

3.2.2. Research Focusing on the Thermal Performance of Walls

Another portion of the reviewed research focused exclusively on the thermal performance of walls or wall samples exposed to fires, elevated temperatures, or in some instances, ambient conditions. Utilising the thermal circuit modelling and nodal point solution method, the impact of concrete density and thermal conductivity was examined on six differently insulated wall assemblies. By varying the placement of the layers of concrete and insulation in relation to each other, the relative thermal performance was established, and conclusions were drawn in terms of the thermal inertia of the assembly. To highlight the impact of the material properties and positioning, two case studies were analysed using commercially available concrete sandwich and insulated concrete form (ICF) units [29]. In keeping with the study of composite sections, a more detailed investigation was dedicated to novel composite concrete panels exposed to fire. The thickness and positioning of the insulation in relation to the fire front was altered, and its impact on the thermal performance of the units was examined both numerically and experimentally. Good agreement between the two was observed, and useful conclusions were drawn relating to the impact of the insulation properties and positioning [30]. Similar information on the type, position, and thickness of insulation for more conventional wall types was sought after using FE modelling. It was shown that such parameters, in conjunction with the emissivity and radiation within perforated masonry units, can severely impact the overall thermal performance of a wall exposed to fire [31].

The impact of emissivity and radiation specifically was considered in a number of research studies. Finite element analysis (FE) modelling was used to establish an equivalent, fictitious material sample reflecting the impact of cavity emissivity and radiation on the thermal performance of walls while simplifying the analytical process for obtaining the results [32]. Acknowledging that the thermal emissivity is not constant, especially when a wall is subject to elevated temperatures, investigations attempted to quantify through FE modelling its impact on the thermal performance of samples by applying a range of coefficient values [33]. Through a computational fluid dynamics (CFD) analysis, it was also established that the size and shape of said cavities affect the amount of radiative and convective heat transfer in autoclaved aerated concrete (AAC) blocks [34]. Utilising similar methods, after identifying a gap in scientific knowledge, an attempt was made to establish the ratio between equivalent thermal conductivity in the vertical and horizontal directions for various brick configurations. Once again, the size and shape of the cavities were shown to affect the vertical heat transfer within the brick wall [35].

Conversely, once the significant contribution of radiative heat transfer within cavities was identified, efforts were made to establish methods of mitigating it. Investigations focused on the impact of applying low-emissivity coatings within masonry unit cavities. Although further studies are needed to confirm the results, the initial findings showed that considerable reductions in the cavity heat transfer can be achieved, improving the wall's overall thermal performance [36]. Furthermore, expanding the toolset for mitigating heat transfer through walls, experimental studies examined the impact of applying renders of different thicknesses by looking at their exposed surfaces. The stability as well as insulating and thermal properties of various samples were examined under applied vertical, mechanical, and fire loads [37].

Some of the reviewed studies focused on heat transfer through masonry walls in ambient conditions. These came to useful conclusions or used methodologies that could be implemented in the more specific application of walls exposed to fire. A combination of experimental results and FE modelling was used to study the thermal performance of concrete block walls. The impact of the unit geometry, concrete mix, and properties of the insulation materials installed in the cavities is part of planned future investigations [38]. A combination of FE modelling and experimental validation was used to understand the contribution of thermal insulation to the thermal performance of concrete block walls. The investigation focused on the density, position, and thermal conductivity of the insulating material [39]. In terms of the material properties' contribution to the thermal behaviour of a wall, an effort was made to correlate the properties of the building units to the overall performance of the wall. Although the properties were considered to be constant, it is planned to repeat the study, taking into consideration their temperature-dependent nature in the future [40].

The behaviour of materials was examined from the angle of regulatory codes as well. The thermal and chemical behaviour of AAC blocks was experimentally investigated with the intention of developing numerical models predicting the temperature of sections when exposed to fire [41]. This study aligned with the aims of simplifying the numerical models and methods proposed by regulatory fire codes (EN 1992-1-2 specifically) by moving towards a more analytical approach utilising an equivalent heat transfer coefficient. This simplified approach has the potential to greatly reduce the amount of calculations and the computational power required to reach an acceptable solution [42].

3.2.3. Studies Carrying out Literature Review

A limited number of the reviewed articles were literature review studies themselves. Despite their small number, the conclusions drawn and points made are of great importance. The performance of masonry assemblies against fire under various testing methods has been the focal point of a range of primary research articles. It was identified that the variation in the testing methods, setups, and sensitivity of various parameters leads to a wide array of material properties available in the bibliography; however, a consolidated knowledge base is still missing. The guidance available on testing masonry in elevated temperatures is still incomplete. The standardisation of results is further hindered by the use of non-standardised testing equipment. This lack of a common testing regimen and equipment leads to an extensive database of experimental results that are difficult to merge, compare, and use as a single resource [43].

As a result of this unregulated pluralism, a holistic understanding of behaviour and critical residual material properties post exposure to fire is difficult to obtain. Focusing on concrete elements under such extreme circumstances, a range of articles have explored the impact of fire exposure, paying special attention to the type of aggregate used. Conclusions have been drawn in relation to the degradation of material properties when exposed to fire, which is correlated with the deterioration in the overall concrete member performance. A similar observation was made that there is a lack of consistent numerical models or formulas taking into account material properties. Researchers use equations based on the specific mixes and heating rates they used in their work, which are not necessarily universally applicable [44].

Approaching the performance of walls exposed to fire from a different angle, reviews and commentaries on current regulatory codes are also necessary. Specifically, the performance criteria relating to the insulation properties of building elements exposed to fire have come under scrutiny. It is considered that the current approach and temperature thresholds on the non-exposed face of walls are unnecessarily conservative, and contemporary research needs to be taken into account to update building codes dating a few decades back [45].

3.2.4. Design Optimisation, Computer Vision, and Statistical Analysis

A number of studies broke away from the trends or areas of research described in previous paragraphs, though they remain, however, within the remit of fire engineering, heat transfer through walls, or other integral building elements. Statistical analysis methods were used to understand and interrogate a results database of extensive façade fire testing. Emphasis was given to the influence the topology and material properties of the façade has on its behaviour when exposed to a fire source. It was highlighted that the power of statistical analysis can extract initially invisible information and patterns when the results of multiple fire tests are combined. It was also acknowledged that machine learning could be used to contribute in this direction [46].

In terms of alternative analysis and monitoring methods, heat release rates, and the consequent impact of fires on facades, computer vision has also been explored. A combination of cameras, algorithms, and visual criteria was used to estimate the volume of a fire plume and correlate it to the heat transferred from a fire source to the adjacent wall. The estimated heat release figures were compared and validated against 3D rendering software with known plume volumes. The method was then calibrated using fire sources with known heat release rates. Being able to estimate the heat release of a fire source through recorded video had multiple benefits in terms of reviewing previous experimental tests (provided they were filmed) and providing an additional powerful tool for interrogating the results of future works [37].

The design optimisation of composite modular partition walls was also examined through the prism of thermal flux. The proposed method was called Inverse Reliability Assessment Method (IRAM), and it was used for identifying the failure point through optimisation before proceeding to find the Reliability-based Design Optimisation (RBDO). This methodology overcame problems encountered by previous processes that came at an increased computational cost or led to unstable convergence results. A numerical case study was presented to showcase the use of the method. The process can be adapted to cater for non-linear or other distribution heat transfer problems [47].

3.3. Current AI Applications in Heat Transfer Research

Examining the use of artificial intelligence in the field of heat transfer through building elements due to fire exposure, a narrower range of studies was identified. Nevertheless, trends and specific areas of scientific interest could be highlighted. These are organized in the following list:

1. Thermal performance assessment of building elements;
2. Optimisation and standardization of design;
3. Hybrid and physics-infused AI models.

The following paragraphs outline the core information obtained through the reviewed primary research, organized according to these themes.

3.3.1. Use of AI for the Assessment of Thermal Performance of Building Elements

A number of scientific investigations focused on obtaining an understanding of the impact a wall's construction type and insulation build-up has on its thermal performance. Examining a range of wall topologies through FE modelling and subsequently feeding the output to artificial neural networks (ANNs) highlighted the potential for predicting the wall's behaviour, minimizing the incurred computational costs. As the use of ANNs is in its infancy, establishing an algorithm development protocol and appropriate metrics for assessing their efficiency and precision is necessary [48]. In alignment with these principles of transparent and reproducible algorithm development, efforts were made to build AI models that were capable of predicting heat transfer through composite steel and concrete floors exposed to a fire from below [49,50]. Hybrid methodologies utilising the Monte Carlo algorithm were also employed in the process of developing more powerful AI models, accurately reflecting the radiative heat transfer phenomenon. Monte Carlo was used to solve the physical problem and to generate data which were then fed as the training input to the ANN. The advantage of such a method was its low computational demands, the high accuracy of its results, and its transparency in terms of its statistical error, allowing for an assessment of the quality of the returned distributions [51].

Sharing the aim of simplifying and reducing the costs of their research methods, other studies tried to mitigate the complexity of the required monitoring equipment by utilising AI tools instead. By only using simple thermocouples and analysing their readings through gradient-boosting decision trees (GBDT), heat flux rates could be predicted by only monitoring the temperature development of a sample [52]. Further simplifying the hardware needed, use of ANNs removed the need for computationally heavy numerical modelling by considering a number of parameters from 1D and 2D models and representative "unit cells" of the structure. ANNs were used to establish coefficients that could represent and accurately describe the out-of-plane performance of a wall [53]. Although this study did not present an application involving a fire scenario, the method and philosophy of using AI would be applicable in other loading situations, including that of extreme heat and fire.

3.3.2. Optimisation and Standardisation of Design

Such opportunities for scientific cross-fertilisation could offer a route towards solving the lack of standardised and overarching methods for the investigation of heat transfer through building elements exposed to fire. Once again, the need for a commonly accepted and regulated method for calculating the residual capacity and material properties of masonry post exposure to fire was pointed out. To develop an appropriate methodology, statistical and ANN models were constructed, ran in parallel, and finally compared with each other. Utilising experimental data previously published in scientific literature, the prediction of the residual compressive capacity of masonry post exposure to fire was made possible without further testing or FE modelling [54]. Instead of trying to understand the performance of walls post fire exposure, other studies tried to optimise their design and thermal behaviour at the specification stage. To facilitate such a task, a combination of FE modelling and genetic algorithms was used, helping to determine the optimum combination of design factors and their values [55].

3.3.3. Hybrid and Physics-Infused AI Models

Experimenting with variations in the conventional ANN algorithm architecture and components, some studies constructed models that were tailored to the specific physical phenomena under consideration. By replacing the commonly used activation functions with physically informed error metrics that satisfy underlying heat transfer partial differential equations, new capabilities were given to the model, converting it to a physically informed neural network (PINN). The greatest benefit from this adaptation was that the PINNs could make predictions beyond their training zone as they were aware of the underlying physics, and they did not only take into account a snapshot of the development of the physical phenomenon based on their limited training dataset [56]. The PINNs were also better placed to solve actual data from physical phenomena which were naturally noisy and possibly incomplete. This created an opportunity for bridging the gaps between the modelling and experimental data, while reducing the required computational power usually involved in detailed simulation models [57].

Apart from noisy or incomplete data, artificial intelligence can help define a heat transfer problem better even in situations in which the parameters of the system are completely unknown. Research utilising a combination of ANNs and FE modelling managed to estimate the boundary conditions of the system. Taking sparse temperature measurements followed by an iterative trial-and-error process enabled the estimation of various parameters of the problem, helping define the boundary conditions of the heat convection and conduction phenomenon [58].

3.4. Studies Using AI Inspire Further Integration in Heat Transfer Research

The final objective of this review was to identify studies using AI in the context of heat transfer in buildings that could offer inspiration for the more specific application of heat transfer through building elements exposed to fire or elevated temperatures. As seen in the previous paragraphs, a large portion of the current research focuses on the investigation of the thermal performance of building elements exposed to fire using techniques other than artificial intelligence. Nevertheless, by a further analysis and comparative study of the obtained information, it was possible to identify relevant scientific applications of machine learning (ML), along with the range of its potential benefits. The following commentary is a result of the concurrent analysis of the conducted review and wider reading undertaken by the reviewing team. The bibliographical references below relate primarily to potential applications that would benefit from the use of AI.

3.4.1. Mitigating the Need for Computationally Heavy Simulations

Several of the reviewed studies resorted to finite element analysis modelling, which often requires considerable computational resources. Artificial intelligence models are capable of learning through existing data of previously conducted work and, as such, mitigate the need for additional modelling [15,20,24]. Techniques such as K-fold validation and the use of a combination of metrics and indexes [48] help researchers assess an AI's output and determine the accuracy and precision of their models [19]. AI also offers the opportunity to widen the scope of conducted research by rapidly performing iterative and multiparametric analyses. Predicting the behaviour of building elements exposed to fire while considering a wide range of factors and variations therein can greatly enhance the breadth of the available research at no considerable extra time and cost [31,32,39,49,50,55]. Existing mathematical models can be used to generate necessary training data, further contributing to the simplification of research [28]. Conversely, it would be of interest to experiment with using AI, genetic algorithms specifically, to simplify existing mathematical models [22,33,42] and use these formulas and models to expedite the design optimisation of building elements [47].

3.4.2. Mitigating the Need for Destructive Testing and Contributing towards Formulation of Mathematical Models

Similarly to modelling output used for training AI models, previously obtained experimental data can be used for training algorithms, reducing the need for costly and environmentally impactful destructive testing. The need for a consistent and universal heat transfer and thermal performance database and models was identified, and AI can aid in this direction [17,21,27,30,40,43–45]. Considerable effort would be required to preprocess the data generated by experiments conducted by different research teams; however, AI could then offer the opportunity to uncover underlying patterns currently unidentified using existing statistical and graphical methods [46]. In instances in which data points are missing, physics-enabled AI models could trawl through noisy or incomplete data and help fill in the gaps [41]. In applications of computer vision, convolutional neural networks, taking advantage of the latest AI developments and algorithm topologies, could enhance the results of existing, more conventional methodologies [59]. Although not encountered in the reviewed articles, a separate branch of investigation utilising computer vision in conjunction with more conventional scientific research methods could focus on the impact of flame colour on heat transfer to surrounding walls. Its potential to affect the dominant heat transfer mechanism is worth exploring further either experimentally or using digital models.

4. Discussion and Conclusions

4.1. Current Research Status and Review Findings

Undertaking a review of the most recent research on the use of artificial intelligence in the field of heat transfer through building elements exposed to fire was of particular interest to us. Underlying investigation patterns, hotspots of scientific interest, and common trends relating to the methodologies followed were identified.

A large portion of the reviewed primary research focused on the combined study of the structural capacity and thermal performance of building elements. The majority of these studies opted for conventional investigation methods: destructive experiments or FE modelling. Alternative methods, including those using statistics, mathematical modelling, or artificial intelligence, were present but limited in use. The AI methods were most commonly experimental in nature, used as a validation tool or as benchmarking for previously conducted experiments or FE models.

Despite the low uptake of artificial intelligence, its potential is high given the commonly accepted need for the development of overarching databases and models. There is a wealth of data, models, and design regulations; however, an urgency to consolidate this fragmented knowledge base has been recognised. AI opens opportunities for reducing the cost, time, and resource requirements of conducting new research. Widening the scope of research or unravelling the underlying information hidden in big data records could boost the scientific community's understanding of the physical phenomena involved in heat transfer through walls, slabs, and structural elements exposed to fire. Despite the potential benefits of using AI, its own drawbacks in terms of data availability, information sharing and organisation, standardisation, and explainability must also be considered and accounted for when planning scientific research.

A limited number of studies have delved into the structural components of AI algorithms and integrated the fundamental principles of the physical phenomena under consideration. This is a field that deserves further investigation since it could lead to the development of specialized AI models with a much greater level of targeted analysis considering fire, heat transfer, and building materials/components.

A need for more targeted research and design principles was also identified on a regulatory level. Researchers are questioning the design thresholds and principles established historically, suggesting that cutting-edge building material technology and research results should be taken into account to update design codes. The overall philosophy of moving towards performance-based design is also a topic of discussion, with scientific teams already acknowledging the potential AI has in enhancing or expediting the transition from more conventional or prescriptive design regulations.

4.2. The Process of Meta-Narrative Review

Beyond the technical observations made by conducting this meta-narrative review, it is worth discussing some aspects of the review process itself. The semi-systematic, meta-narrative review is considerably less utilised than the common meta-analysis approach. Depending on the nature of the reviewed content, the meta-narrative opens different opportunities for researchers to view the "bigger picture" of their area of interest without necessarily investing disproportionate amounts of resources in granular statistical analyses and numbers reviews. A strict review protocol is necessary, to ensure not only a consistent and transparent review process but also one that can be repeated and scrutinised by researchers in the future. As part of this disciplined approach, a primary research scoring system needs to be in place.

In this instance, a large number of the obtained scientific studies were subsequently rejected on the grounds of relevance and/or the quality of their methodology presentation. In terms of relevance, the question arises whether sourcing research for reviews based on titles and keywords only is efficient. Although it proves efficient at the first stage of the review, a significant amount of time is required to review and reject/accept articles in the second phase. With the rise of AI technologies capable of text recognition, synthesis, and analysis before search results are returned, it is worth considering whether a new approach in scientific text search is becoming available. At the second stage of the primary research filtering, a considerable number of papers were rejected on the grounds of poor methodology presentation. The number of studies failing to clearly present their method or omitting details necessary for reproducing the experiments or modelling process was concerning.

4.3. Future Research Directions

Although interesting conclusions were drawn through this review, its main goal was not to set an ultimatum but instead to initiate a dialogue and stimulate fresh thinking in the way research is conducted in the field of heat transfer due to fires in buildings. In light of the above outcomes, future research efforts will focus on establishing appropriate work protocols both for the development of machine learning algorithms and their implementation in heat transfer research.

Transparency, completeness, and reproducibility of the process should be at the core of any new research that aims to establish AI as a beneficial analysis tool in this field. Given the relatively low current uptake of AI, it is our intention to integrate such methodologies further in applications of heat transfer through load-bearing or partition walls exposed to fires and/or elevated temperatures. Additionally, we intend to construct databases utilising information obtained through previous experiments, CFD analyses, and published literature to enable the development of appropriately trained AI models.

5. Conclusions

Considering the valuable information obtained while reviewing the wide range of primary research, and in conjunction with the discussion of the previous paragraphs, a number of important conclusions can be made. The following list will hopefully encourage a dialogue and will certainly stimulate new ideas given the extremely active field of artificial intelligence.

- The study of building members exposed to fire most commonly focuses on a combined investigation of thermal and structural behaviour;
- There is currently only a limited use of artificial intelligence, which is most commonly used either as a secondary tool or to complement more conventional thermal modelling or destructive fire testing methods;
- There is a widely accepted need for the consolidation of the existing fragmented knowledge base and fire testing experimental data records;
- There is a need for overarching models describing the phenomena involved in heat transfer through building members exposed to fire;
- AI opens opportunities for widening the scope of scientific research and uncovering underlying trends in already obtained data;
- Integrating the basic principles of the heat transfer phenomena into AI algorithm topologies can enhance and expand their use and effectiveness;
- AI has the potential to expedite the transition towards performance-based design codes and regulations.

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