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Evaluating and Ranking Simulation Tools for Railway Fire Safety with the Analytic Hierarchy Process

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Abstract

Fire safety in railway systems requires reliable and validated tools capable of reproducing both the physical dynamics of fire and the behavioral responses of passengers. Conducting full-scale evacuation drills is prohibitively expensive, logistically complex, and often unsafe, which makes advanced numerical modeling an indispensable alternative for research and engineering practice. Numerical modeling has therefore become a practical alternative, but the diversity of available software makes tool selection challenging. This study applies the Analytic Hierarchy Process (AHP) to evaluate and rank simulation platforms according to a comprehensive set of technical, regulatory, and operational criteria specifically tailored to railway fire safety. Four widely used tools (PyroSim/FDS, Pathfinder, STEPS, and EXODUS) were compared. Results show that PyroSim/FDS is the preferred option for fire and smoke analysis, regulatory compliance, and validation, while Pathfinder excels in evacuation modeling and usability. Other tools show average performance compared to these leading platforms. Sensitivity analysis demonstrates that rankings vary when ergonomics or cost are prioritized, highlighting the importance of weight assignment in AHP. The study contributes a transparent framework for tool selection in railway fire safety, combining regulatory standards, empirical evidence, and expert judgment. Beyond individual rankings, the findings suggest a best-in-class approach that integrates fire and evacuation modeling. This methodology strengthens confidence in simulation-based safety decisions and supports performance-based engineering in railway contexts.

Keywords: *AHP, fire, numerical modeling, Pyrosim/FDS, railway.*

1 Introduction

Railway fire safety poses unique challenges due to the confined geometry of passenger trains, the diversity of materials involved, and the complexity of evacuation dynamics. Traditional large-scale evacuation exercises, while informative, remain impractical in routine practice because of their high cost, organizational burden, and inherent risks [1][2][3]. As a result, simulation platforms have become essential instruments, offering a controlled environment to analyze fire growth, smoke propagation, and passenger behavior with reproducibility and scientific rigor.

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Several simulation environments have been developed to support fire safety engineering, such as PyroSim/FDS for fire and smoke modeling [4][5]. The emergence of such tools dates back to the second half of the twentieth century, initially based on analytical equations and later evolving into numerical models as computing power and knowledge of fire phenomena advanced. Recently, immersive technologies such as virtual reality have been used alongside numerical fire modeling. They are used for training and visualisation, but not as main simulation techniques [6][7]. Numerical fire models have advanced more slowly than in other engineering areas, such as mechanics, mainly due to the complexities of modeling fire. The tight coupling of transport, heat and chemistry processes complicates its modeling [8]. The recent advancement is mainly driven by the development of performance based fire safety engineering, as defined in ISO 23932 [9], which offers a formal method to achieve compliance with safety regulations in both transportation and buildings [10]. A number of numerical models have evolved [11][12]. Kuligowski and Gwynn [13] have developed a framework for practitioners' choice of fire models. They stress that there is no "one size fits all" model; the selection of fire model must be mindful of the purpose of analysis, the desired detail, and user constraints such as computing power, user knowledge, and regulatory considerations. This framework has five dimensions:

- Analysis purpose: research, forensic, regulation, and design.
- Capabilities: fire, smoke, gas, human.
- Simplicity vs. sophistication: using the more complex CFD models and the simpler zone models.
- Validation and acceptance: experimental data, and acceptance by standards like NFPA 130 [14] or ISO 23932 [9].
- Cost factors: computing resources, software, training

This framework, defined as a decision support canvas, aligns tool choice with technical needs and institutional needs. It is relevant to railway fires.

Against this background, the present study introduces the Analytic Hierarchy Process (AHP) as a structured methodology for evaluating and ranking simulation platforms in railway fire safety. The motivation lies in the absence of a standardized approach for tool selection, despite the diversity of available platforms and the critical importance of regulatory compliance and operational reliability.

The contributions of this work are twofold:

- Establishing a transparent and reproducible framework that formalizes tool selection by integrating technical, regulatory, and operational dimensions.
- Demonstrating, through comparative analysis and sensitivity testing, how AHP supports informed decisions and highlights the relative strengths of leading platforms.

Building on the decision-support canvas proposed by Kuligowski and Gwynn, this research extends their framework by applying AHP to railway-specific contexts.

The remainder of this paper is organized as follows: Section 2 introduces the AHP methodology, Section 3 reports the main findings, Section 4 provides a discussion of the results and rankings, and Section 5 concludes with perspectives for future research.

For clarity, terminology is defined as follows: *model* refers to the mathematical representation of fire or evacuation phenomena (e.g., FDS as a CFD model); *software* denotes the executable program implementing the model; *tool* designates a practical application used by engineers (e.g., Pathfinder for evacuation); and *platform* indicates an integrated environment combining multiple tools or components (e.g., PyroSim as a GUI for FDS).

2 Methodology

2.1 AHP method

The Analytic Hierarchy Process (AHP) method, developed by Saaty [15], is a decision-making approach to handling complex, multi-criteria problems. It is a hybrid of qualitative and quantitative decision-making methods that uses a mathematical framework that is easy to understand. AHP's flexibility and robustness has led to its use in many engineering, management and safety studies. The process involves a number of steps:

- **Step 1 – Hierarchical Structure**: The decision problem is structured. The highest level is the goal - to choose the simulation tool. In the middle are the decision criteria and where appropriate, sub-criteria that further define them. At the bottom are the decision alternatives, in this case the candidate tools. This format provides clarity and allows an objective and transparent evaluation.
- **Step 2 – Pairwise Comparisons**: Criteria (and later alternatives) are compared two at a time using Saaty's fundamental scale, which ranges from 1 (equal importance) to 9 (extreme importance). Intermediate values allow for nuanced judgments. Table 1 provides a detailed explanation of this scale.

Table 1: The 1–9 scale for pairwise comparisons

Intensity of importance	Meaning
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments

The outcome of this step is a square matrix $A=(a_{ij})$, where each element aij represents the importance of element i relative to element j. Reciprocity is enforced, meaning $a_{ij}=1/a_{ji}$.

- **Step 3-Derivation of Weights Using Eigenvalue Analysis**: Relative weights are obtained by calculating the principal eigenvector w of the comparison matrix. This vector reflects the normalized priorities of each criterion. In practice, approximation methods such as column normalization followed by averaging row values are often used.
  - **Eigenvector Calculation**

For each column j of matrix A, the sum is calculated as:

$$Sj = \sum_{i=1}^{n} a_{ij} \tag{3}$$

Then each element is normalized as:

$$ã_{ij} = \frac{a_{ij}}{Sj} \tag{4}$$

The normalized matrix Ã thus has columns whose sums equal 1.

The weight associated with criterion C_i is obtained by calculating the average of the elements in row i of the normalized matrix:

$$w_i = \frac{\sum_{j=1}^{n} ã_{ij}}{n} \tag{5}$$

This operation corresponds to an approximation of the principal eigenvector of the initial matrix.

- **Maximum Eigenvalue λ_{max}**

The first step consists of multiplying matrix A by the normalized eigenvector w, then dividing each component of the resulting vector by the corresponding component of w. The average of these values provides an estimate of λ_{max}:

$$\lambda_{\max} = \left(\frac{1}{n}\right)\left(\frac{\sum_{i=1}^{n} Aw_i}{w_i}\right) \quad (6)$$

For a perfectly consistent matrix, λ_{max}=n. Any deviation indicates a certain level of inconsistency.

- **Step 4-Consistency Verification:** Since pairwise comparisons are based on subjective judgments, it is essential to check their logical consistency. The consistency index (CI) is computed from the largest eigenvalue λ_{max} of the matrix, using the formula:

  $$\mathrm{CI} = \frac{\lambda_{\max} - \mathrm{n}}{\mathrm{n} - 1} \quad (7)$$

  where n is the matrix dimension. The consistency ratio (CR) is then obtained by the formula:

  $$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad (8)$$

  The RI is the average random consistency index, which is independent of attribute values and varies for a different number of attributes. The average random consistency index of an n order matrix is illustrated in Table 2.

  Table 2: Random Index RI values

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

  A CR value below 0.10 is generally considered acceptable, indicating that the judgments are coherent.

- **Step 5-Aggregation of local and global priorities**: Once weights are established, alternatives are evaluated against each criterion using pairwise comparisons. Local priorities (scores relative to each criterion) are multiplied by the corresponding criterion weights. Summing these products yields the global priority of each alternative. The option with the highest global score is identified as the optimal choice.

2.2 Criteria for tool selection

Building on the qualitative framework proposed by Kuligowski and Gwynn [13], which emphasizes tool selection according to user needs, this study translates their dimensions into quantifiable criteria tailored to railway fire safety. Their canvas highlights modeling capabilities, usability, validation, and resource constraints. Our AHP approach turns these elements into eight criteria:

- C1 – Physical modeling of fire and smoke
- C2 – Adaptation to the railway context
- C3 – Evacuation modeling
- C4 – Regulatory compliance
- C5 – Scientific validation
- C6 – Ergonomics and visualization
- C7 – Cost and implementation complexity

- C8 – Fire–evacuation coupling.

This mapping ensures methodological continuity while extending the framework to address the specific challenges of railway systems, where compliance with international standards and the integration of fire and evacuation dynamics are critical.

Table 3 shows the mapping of the qualitative axes of Kuligowski and Gwynn with the quantitative AHP criteria used in this work.

Table 3: Mapping the framework: Kuligowski & Gwynn vs. AHP criteria

Kuligowski & Gwynn Selections	AHP Criteria	Explanatory Link
Analysis Purpose	C2- Fit for purpose in the railway environment C4- Standards compliance	Ensures the tool selection is appropriate for railway-specific applications and compliant with international standards.
Modeling capabilities	C1- Fire and smoke physical modeling C3- Evacuation modeling C8- Fire/evacuation coupling	Describes the capacity of the software to simulate complex physical and behavioural events, including fire/evacuation scenarios.
Complexity vs. usability	C6- Ergonomics and visualization	Considers the user-friendliness, interface clarity and visualization tools that assist in understating the results.
Validation and credibility	C5 – Scientific validation	Verifies the robustness of the model through experimental validation and institutional acceptance.
Resource requirements	C7 – Cost & implementation complexity	Measures the cost and complexity of purchase, training and hardware/software needs.

The choice of the eight criteria (C1–C8) was not arbitrary. It reflects a systematic alignment with both international standards and the operational realities of railway fire safety. The criteria (C1-C8) were carefully selected. It is a comprehensive approach to conform both to international standards and to operational railway fire safety. The criteria align to the factors explicitly considered in the literature or codes:

- C1 - Fire and smoke physics: Visibility, temperature and toxicity limits are important in NFPA 130 and ISO 23932, the physics of fire and smoke should be correct.
- C2 - Railway adaptability: Geometry, compartmentalization and materials of the train affect the egress time and the fire, so railway adaptability is important.
- C3 - Evacuation simulation: People movement, bottlenecks and behaviour is key to evacuations, research shows.
- C4 - Code compliance: Compliance with NFPA 130 and ISO gives institutional and operational validity.
- C5 - Scientific verification: Verification against experiments and standards ensure the validity of the results.
- C6 - User interface and visualization: Usability and visualisation are important for practitioners to interpret simulation results and communicate to others.
- C7 - Cost and effort: Licensing, training and computational requirements are critical for implementation.

- C8 - Integrated fire-evacuation: Fire- and evacuation-modelling is required to account for the effect of smoke on passengers.

These are the smallest set of criteria representing both the technical and institutional dimensions of railway fire safety. While many sub-criteria can be identified, our research shows that these eight dimensions cover all the dimensions identified in standards, empirical evidence and practice.

Beyond transforming qualitative dimensions into quantitative criteria, this paper also offers a new perspective on the application of AHP for railway fire safety. First, the pairwise comparisons process was made explicit in relation to the operational context and empirical evidence about passenger evacuation. Second, rather than simply reporting weights, the process involves a sensitivity loop: after calculating eigenvectors we test new weight distributions to determine how they affect the ranking. This provides transparency and confidence, as we demonstrate, for example, that Pathfinder becomes more important when ergonomics and cost are prioritised.

2.3 Alternatives

We started the search for simulation tools for railway fire safety with a survey of existing platforms. Software at early stages of development, not actively developed, or missing key features was removed. Similarly, tools lacking fire or evacuation modules were rejected as external linking or conversion would introduce more complexity.
We then excluded those that were not popular and institutionally accredited tools, and those that did not have integrated functionalities for fire, smoke and people movement. Four such platforms were chosen for their purpose, availability and popularity in research and practice:

- PyroSim/FDS - PyroSim is a front-end to the Fire Dynamics Simulator (FDS) software, developed by NIST [16]. FDS uses a field model based on the Navier-Stokes equations to model fire-induced fluid flow. This model offers detailed results on temperature, smoke and toxic gases, and is well validated.
- Pathfinder - Pathfinder is an evacuation simulation model that simulates occupant movement in emergency situations [17]. It has enhanced graphics and can be linked with fire simulations in FDS for fire-evacuation modeling.
- STEPS - Mott MacDonald developed STEPS (Simulation of Transient Evacuation and Pedestrian movementS), which is a model of pedestrian movement and evacuation in complex systems such as transport networks, tunnels and buildings [18].
- EXODUS - EXODUS is an evacuation code from the University of Greenwich widely used in transport and buildings. It has behavioural algorithms for decision making, route choice and crowd flow during an emergency [19].

Other CFD software, like ANSYS Fluent and OpenFOAM, are also capable of combustion and smoke simulations. Fluent's turbulence, combustion and radiation models are advanced, with sophisticated meshing and multiphysics capabilities. But it is expensive and complex, restricting its application in regular railway safety analyses and not fire specific. OpenFOAM, on the other hand, is open source and offers flexibility, can manage large meshes and has a strong research background. But its complexity, user-defined validation, and lack of institutionalized workflows limit its institutional use in railway certification.

In comparison, FDS (using PyroSim or other GUI versions) is the de facto standard in fire CFD for railway safety. It is fire-specific, well-validated by NIST and accepted within the industry. Although it is less versatile for multiphysics simulations, its versatility and adoption by institutions justify the focus of this study on FDS/PyroSim.

3 Results

3.1 Matrice AHP

Matrix 1(A) ranks the eight criteria chosen to assess simulation tools. The rows represent the importance of a criterion Ci in relation to the other criteria Cj, based on Saaty's fundamental scale.

$$A = \begin{bmatrix} 1 & 2 & 3 & 1 & 2 & 3 & 4 & 5 \\ \frac{1}{2} & 1 & 2 & 1 & 2 & 2 & 3 & 4 \\ \frac{1}{3} & \frac{1}{2} & 1 & \frac{1}{2} & 1 & 2 & 2 & 3 \\ 1 & 1 & 2 & 1 & 2 & 2 & 3 & 4 \\ \frac{1}{2} & \frac{1}{2} & 1 & \frac{1}{2} & 1 & 2 & 2 & 3 \\ \frac{1}{3} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & 1 & 2 & 2 \\ \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & \frac{1}{3} & \frac{1}{2} & \frac{1}{2} & 1 & 2 \\ \frac{1}{5} & \frac{1}{4} & \frac{1}{3} & \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & \frac{1}{2} & 1 \end{bmatrix}$$

Matrix 1: Pairwise Comparison Matrix

The criteria are ordered as follows:

(C1,C2,C3,C4,C5,C6,C7,C8)=(Fire/Smoke Modeling, Railway Adaptation, Evacuation, Regulatory Compliance, Validation, Ergonomics, Cost, Fire–Evacuation Coupling).

In our study, we have set up pairwise comparisons according to the realities of railway operations. This was done to reflect the true priorities of fire protection in passenger trains. Thus, criteria that address fire physics (C1), fit for rolling stock (C2) and conformity with regulations (C4) were consistently positioned at the highest level. Past research [20] show that visibility, smoke spread and door arrangements are factors that affect the safe egress time.

On the other hand, criteria such as ergonomics (C6), cost (C7), and fire–evacuation coupling (C8) were systematically prioritised as less important, as these do not influence passenger safety and regulatory compliance. Thus, the AHP rankings reflect a logical hierarchy based on field experience, normative aspects and experimental findings.

Comparisons were made on the basis of the technical features of each software, railway relevance, scientific validation, and its role in a fire–evacuation simulation chain. To ensure consistency with expert opinions, each alternative was associated with at least one scientific or technical reference. For the eight criteria (C1-C8) considered, the main literature sources used to establish the relative rank of the four tested tools are summarised in Table 4.

Table 4 – Scientific references by criterion and alternative

Criterion	PyroSim/FDS	Pathfinder	STEPS	EXODUS
C1 – Fire/Smoke Modeling	Ref.:[16]	Ref.:[21]	Ref.:[18]	Ref.:[19]
C2 – Railway Adaptation	Ref.:[16]	Ref.:[17]	Ref.:[18]	Ref.:[19]
C3 – Evacuation Modeling	Ref.:[16]	Ref.:[21]	Ref.:[18]	Ref.:[22]
C4 – Regulatory Compliance	Ref.:[16]	Ref.:[17]	Ref.:[18]	Ref.:[19]
C5 – Scientific Validation	Ref.:[16]	Ref.:[21]	Ref.:[23]	Ref.:[19]
C6 – Ergonomics & Visualization	Ref.:[16]	Ref.:[17]	Ref.:[18]	Ref.:[19]
C7 – Cost & Implementation Complexity	Ref.:[16]	Ref.:[21]	Ref.:[23]	Ref.:[19]
C8 – Fire–Evacuation Coupling	Ref.:[16]	Ref.:[21]	Ref.:[18]	Ref.:[19]

To enhance the transparency of the pairwise comparisons, the justification of the judgement is rephrased in Table 5. The table establishes the connection of each criterion to operational considerations for railway fire safety, regulatory considerations, and empirical evidence for prioritisation. This format guarantees that the weights are not only transparent but also consistent with standards and practice. Through the links to specific references and practice, the table shows that the prioritisation is not an arbitrary decision, but reflects technical and institutional realities.

Table 5 – Criteria and rationale for judgments

Criterion	Rationale for judgment	Operational/Empirical Basis
C1 – Fire/Smoke Modeling	Prioritized because smoke propagation, visibility, and toxicity directly determine survivability.	NFPA 130 visibility thresholds; ISO 23932 smoke spread; experimental data showing smoke as the main factor limiting safe egress time.
C2 – Railway Adaptation	Essential for representing train geometry, compartments, and materials.	Rolling stock design standards; studies on door configuration and inter-car connections affecting evacuation.
C3 – Evacuation Modeling	Critical for capturing passenger flow, bottlenecks, and behavior.	Empirical evacuation drills; agent-based modeling literature; studies on passenger rail egress.
C4 – Regulatory Compliance	Ensures institutional acceptance and credibility of results.	EN 45545 fire safety requirements; TSI standards; NFPA 130 compliance for visibility and temperature.
C5 – Scientific Validation	Guarantees reliability of simulations through benchmarking.	V&V programs for FDS; comparative evacuation model validations; international benchmark datasets.
C6 – Ergonomics & Visualization	Important for usability and communication of results to stakeholders.	Industry practice requiring clear 2D/3D visualization for decision-makers; ergonomic interfaces reduce training time.
C7 – Cost & Implementation Complexity	Influences adoption in real projects under budget constraints.	Licensing costs, computational demand, and expertise required; practical feedback from railway operators.

Criterion	Rationale for judgment	Operational/Empirical Basis
C8 – Fire–Evacuation Coupling	Necessary to capture interactions between smoke conditions and passenger movement.	Case studies showing evacuation times vary significantly when smoke visibility fields are integrated into evacuation models.

3.2 Calculation of the eigenvector

The eigenvalue of the AHP matrix was obtained by normalising the columns of the matrix as proposed by Saaty [15]. The weighting vector is:

$$w = \{0.24, 0.17, 0.11, 0.19, 0.11, 0.08, 0.06, 0.04\}$$

These weights reflect the importance of the criteria:
- C1 (Fire/Smoke Modeling) is the most important (24%).
- C2 (Railway Adaptation) and C4 (Regulatory Compliance) are next (17% and 19%).
- C3 (Evacuation) and C5 (Validation) are of average importance (11%).
- C6 (Ergonomics), C7 (Cost) and C8 (Fire - Evacuation Coupling) are less critical.

3.3 Evaluation of alternatives

Pair-wise comparisons were made between the alternatives for each criterion.
Results show :
- PyroSim/FDS is the preferred choice for fire (C1), railway (C2), regulation (C4), validation (C5), and fire combined with evacuation (C8).
- Pathfinder dominates in evacuation modeling (C3), ergonomics (C6) and implementation cost (C7).
- STEPS and EXODUS are average performers, but EXODUS is lowest in C2 due to its historical use in aeronautical/maritime and lack of railway specific testing.

Complete pairwise matrices and justifications are in Appendix A.

3.4 Aggregation of scores and sensitivity analysis

As shown in Table 6, the results show that, within the scope of tools used to conduct fire safety analysis of railway stations, PyroSim/FDS is the preferred tool.

Table 6 : Global scores of alternatives obtained by the AHP method

Alternative	Global Score
PyroSim/FDS	0.48
Pathfinder	0.26
STEPS	0.15
EXODUS	0.11

To demonstrate the robustness of the results, a sensitivity analysis was carried out by changing the weight of the criteria (As shown in Table 7). The aim is to measure the impact of shifting priorities to the tool ranking.

Table 7 – Sensitivity scenarios and global scores

Scenario	PyroSim/FDS	Pathfinder	STEPS	EXODUS	Ranking Outcome
Baseline (C1=0.24, C4=0.19)	0.48	0.26	0.15	0.11	PyroSim/FDS > Pathfinder > STEPS > EXODUS
Scenario A – Emphasis on Evacuation (C3=0.20)	0.34	0.39	0.15	0.12	Pathfinder > PyroSim/FDS > STEPS > EXODUS
Scenario B – Emphasis on Ergonomics & Cost (C6=0.15, C7=0.12)	0.42	0.41	0.10	0.07	PyroSim/FDS ≈ Pathfinder > STEPS > EXODUS
Scenario C – Reduced Fire Modeling Importance (C1=0.15)	0.36	0.33	0.18	0.13	PyroSim/FDS > Pathfinder > STEPS > EXODUS (closer gap)
Scenario D – Emphasis on Validation (C5=0.20)	0.44	0.28	0.15	0.13	PyroSim/FDS > Pathfinder > STEPS > EXODUS

- The default scenario (above) results in PyroSim/FDS being the preferred choice, given the emphasis on fire/smoke modeling and code compliance.
- Prioritizing evacuation (C3) makes Pathfinder the top tool, due to its agent based evacuation modeling.
- Emphasis on user-friendliness and cost (C6, C7) sees Pathfinder almost tied with PyroSim/FDS, demonstrating the influence of ease-of-use and affordability.
- When fire modeling (C1) is de-emphasized, PyroSim/FDS and Pathfinder are closer and STEPS/EXODUS show a slight improvement.
- When scientific validation (C5) is prioritized, this further entrenches PyroSim/FDS, given its rigorous experimental testing.

This sensitivity analysis shows the results are not rigidly in favour of PyroSim/FDS, but reflect the weight given to safety critical criteria. The anchoring of pairwise comparisons in regulatory and empirical standards, and the stability of the rankings with different weights, enhance confidence in the results, while the subjectivity of expert judgements is clearly acknowledged in the AHP methodology.

4 Discussion

PyroSim/FDS is the preferred software for railway fire safety analysis, according to the analysis. This is due to its strong fire/smoke modeling, compliance with regulations and its proven track record. Pathfinder comes second due to its capabilities in evacuation modelling and user friendly interface. On the other hand, STEPS and EXODUS are placed further down, due to their lack of flexibility with regards to railway specific settings and their limited interaction with fire simulations based on CFD software.

One notable finding is that the ranking is heavily influenced by the weightings of the criteria. The heavy weighting of fire/smoke simulation (C1 = 0.24) and compliance with regulations (C4 = 0.19) obviously advantaged PyroSim/FDS. In contrast, ergonomics (C6

= 0.08) and cost (C7 = 0.06) weighed less. This suggests that the decision-making process favoured safety critical criteria (visibility, smoke movement and regulatory compliance).

The findings also demonstrate the importance of criteria selection and weighting in AHP. An alternative weighting, such as placing more emphasis on ergonomics or cost, would have resulted in a different ranking with Pathfinder favoured. This highlights the importance of setting up the framework of analysis and ensuring that the weights are based on operational insight and expert opinion.

Beyond the rankings, the composite scores suggest a best in class approach to fire and evacuation modeling: using PyroSim/FDS for fire and smoke simulations, and Pathfinder for evacuation. Together, they offer a full suite of tools for fire safety in railways. FDS provides reliable CFD results for smoke, heat and toxicity, and Pathfinder models passenger response to a changing environment. The integration of both allows for evaluation of the available safe egress time (ASET) and required safe egress time (RSET), and the consideration of a full model of fire and human behaviour in design and operational decisions. This approach is well accepted in regulatory applications and provides confidence in the results obtained from the AHP analysis.

On the other hand, a critical appraisal is required of the AHP method itself. Although AHP provides a structured approach to multicriteria decision making, it may hide dissent among the experts because the individual opinions are summed up in a single matrix. Further, the reliance on Saaty's 1-9 scale may create artificial differences among criteria, where experts may not see them as being so different. This indicates that other approaches, such as fuzzy AHP or other multicriteria methods, may be more appropriate in situations with a greater number of alternatives or where capturing uncertainty and disagreement among experts is important.

5 Conclusions

The present study has shown the usefulness of the Analytic Hierarchy Process (AHP) as a multi criteria approach to tool selection in railway fire safety simulations. The approach was successful and feasible, providing transparency for ranking and consistency testing of expert opinions. However, its dependence on the weighting of criteria also underlines the need for well-defined and justified selection criteria.

For increased confidence and diversity, future work could explore integration with other methods of decision making that reflect uncertainty or different preference structures. For example, TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) or PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation). Such methods would allow for sensitivity testing and cross validation, hence strengthening confidence in tool selection for safety critical applications.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix A-Detailed Pairwise Comparison Matrices

Alternative assessment is based on the pairwise comparison of each simulation tool for each of the criteria defined in the AHP hierarchy. For all criteria, the alternatives are compared in a pairwise comparison matrix:

C1 – Fire Modeling

PyroSim/FDS is the best rated software for this criterion as it is the state-of-the-art fire simulation software based on Computational Fluid Dynamics (CFD). It allows the detailed representation of smoke dynamics, radiative transfer, combustion, heat transfer and their interaction with structures. This fine-level representation of physical processes makes it the ideal software to investigate fire scenarios in the railway sector. On the other hand, Pathfinder and STEPS do not have integrated fire modules and must be coupled with other programs to represent thermal effects, making them less interesting for a full risk assessment. EXODUS includes some fire-related modules, but not with such detail and resolution as allowed by CFD. These aspects justify the choice of PyroSim/FDS for this criterion. Matrix 2 (A_{C1}) shows pairwise comparison matrix for Criterion C1:

$$A_{C1} = \begin{bmatrix} 1 & 9 & 7 & 7 \\ \frac{1}{9} & 1 & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{7} & 3 & 1 & 1 \\ \frac{1}{7} & 3 & 1 & 1 \end{bmatrix}$$

Matrix 2 : Evaluation of criterion C1

C2 – Adaptation to the Railway Context

PyroSim/FDS is deemed clearly the best of the tools, since it can model the geometry, compartmentalization, interconnections and the materials of the passenger cars. Pathfinder and STEPS give accurate representation of evacuation routes in trains, but are less flexible in modeling technical spaces. Lower score for EXODUS because it was originally developed for the aeronautical and maritime domains; it does not have native modules for train geometry, compartmentalization or EN 45545 compliance. Furthermore, it has no empirical basis for train evacuations. Matrix 3 (A_{C2}) shows pairwise comparison matrix for Criterion C2:

$$A_{C2} = \begin{bmatrix} 1 & 3 & 3 & 5 \\ \frac{1}{3} & 1 & 1 & 3 \\ \frac{1}{3} & 1 & 1 & 3 \\ \frac{1}{5} & \frac{1}{3} & \frac{1}{3} & 1 \end{bmatrix}$$

Matrix 3 : Evaluation of criterion C2

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C3 – Evacuation Modeling

Pathfinder is rated significantly better than other software, as it combines advanced agent-based models, speed control, bottlenecks and individual characteristics. STEPS and EXODUS also have evacuation features, but with less ergonomics and integration for the railway system. PyroSim/FDS is not for dynamic evacuation models, hence a very low mark. Matrix 4 (A_{C3}) shows pairwise comparison matrix for criterion C3:

$$A_{C3} = \begin{bmatrix} 1 & \frac{1}{9} & \frac{1}{3} & \frac{1}{3} \\ 9 & 1 & 4 & 4 \\ 3 & \frac{1}{4} & 1 & 1 \\ 3 & \frac{1}{4} & 1 & 1 \end{bmatrix}$$

Matrix 4 : Evaluation of criterion C3

C4 – Regulatory Compliance

FDS is broadly applied in fire safety engineering and allows compliance with the visibility, temperature and toxicity criteria to be demonstrated. Pathfinder can also be used to calculate evacuation times (RSET). STEPS and EXODUS are scientifically valid but are less commonly used for demonstrations to railway regulations, hence their lower priority. Matrix 5 (A_{C4}) shows pairwise comparison matrix for criterion C4:

$$A_{C4} = \begin{bmatrix} 1 & 3 & 4 & 5 \\ \frac{1}{3} & 1 & 2 & 3 \\ \frac{1}{4} & \frac{1}{2} & 1 & 2 \\ \frac{1}{5} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix}$$

Matrix 5 : Evaluation of criterion C4

C5 – Scientific Validation

FDS has a large validation base, including experimental validations and international comparisons. Pathfinder has a good validation for evacuation models. STEPS and EXODUS provide good validation, but less well documented in the railway industry, hence lower scores. Matrix 6 (A_{C5}) shows pairwise comparison matrix for criterion C5:

$$A_{C5} = \begin{bmatrix} 1 & 3 & 5 & 5 \\ \frac{1}{3} & 1 & 3 & 3 \\ \frac{1}{5} & \frac{1}{3} & 1 & 1 \\ \frac{1}{5} & \frac{1}{3} & 1 & 1 \end{bmatrix}$$

Matrix 6 : Evaluation of criterion C5

C6 – Ergonomics and Visualization

Pathfinder is rated the best with good ergonomics, 2D/3D visualizations and good communication. PyroSim/FDS has good ergonomics but is more technical. STEPS and EXODUS are considered difficult to use, with a high learning curve. Matrix 7 (A_{C6}) shows pairwise comparison matrix for criterion C6:

$$A_{C6} = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{2} & 3 \\ 3 & 1 & 4 & 5 \\ 2 & \frac{1}{4} & 1 & 2 \\ \frac{1}{3} & \frac{1}{5} & \frac{1}{2} & 1 \end{bmatrix}$$

Matrix 7 : Evaluation of criterion C6

C7 – Cost and Complexity

Pathfinder strikes an excellent balance between cost, licensing and implementation. STEPS and EXODUS have high costs or implementation complexity. PyroSim/FDS is a powerful tool but requires more advanced CFD modeling skills, and is thus more complex. Matrix 8 (A_{C7}) shows pairwise comparison matrix for criterion C7:

$$A_{C7} = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ 3 & 1 & 2 & 2 \\ 3 & \frac{1}{2} & 1 & 1 \\ 3 & \frac{1}{2} & 1 & 1 \end{bmatrix}$$

Matrix 8 : Evaluation of criterion C7

C8 – Fire–Evacuation Coupling

PyroSim/FDS is clearly the best as it outputs the physical fields (temperature, smoke, visibility) needed for evacuation modeling. Pathfinder has excellent coupling capabilities, as it imports FDS results. STEPS and EXODUS have limited coupling capabilities, and are not as well aligned with the regulatory processes and operational procedures usually required for railway safety demonstration, which explains the lower marks. Matrix 9(A_{C8}) shows pairwise comparison matrix for criterion C8:

$$A_{C8} = \begin{bmatrix} 1 & 3 & 7 & 7 \\ \frac{1}{3} & 1 & 5 & 5 \\ \frac{1}{7} & \frac{1}{5} & 1 & 1 \\ \frac{1}{7} & \frac{1}{5} & 1 & 1 \end{bmatrix}$$

Matrix 9 : Evaluation of criterion C8