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Comparative Safety Assessment of Prescriptive Means-of-Egress Configurations Using Fault Tree Analysis

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Abstract

Prescriptive building regulations commonly permit several means-of-egress and rescue configurations that satisfy the same regulatory safety objectives without explicitly quantifying whether these configurations provide comparable safety. This study develops a comparative fault tree analysis (FTA) framework and applies it to 21 residential means-of-egress configurations derived systematically from the German Model Building Code and related provisions. A common top event is defined as an acute fire service rescue being required before fire extinguishment outside the fire dwelling. The models contain 93 basic-event input values. All 93 inputs are assigned ex ante by expert judgement using a seven-level, ordinally anchored numerical likelihood scale, with five deliberately selected intermediate values where finer differentiation was required. They are therefore interpreted as comparative numerical likelihood inputs rather than empirically validated failure probabilities. The objective of the study is not to establish consensus probabilities but to investigate whether differences emerge under a consistently applied expert-based assessment framework. The resulting top-event metric is consequently reported as an FTA-derived score. Across all 21 configurations, the score ranges from 0.274 to 0.852. More importantly, among the 14 standard-code configurations that are treated as regulatory alternatives, the range is 0.477 to 0.809, corresponding to a comparative score ratio of 1.70. A monotonic scale-transformation analysis shows high rank stability (Spearman $\rho = 0.986$–0.999; Kendall $\tau = 0.952$–0.990). The results demonstrate that prescriptively admissible configurations can contain materially different implicit safety margins. The framework is intended as a transparent comparative screening method for regulatory analysis, not as an estimator of absolute fire-event probabilities.

Keywords: Fault tree analysis, Means-of-egress, Fire risk, Fire safety engineering, Prescriptive regulation, Comparative safety assessment, Residential buildings, Fire service, Expert judgement

1 Introduction

Building fire safety regulations must convert broad safety objectives into design rules that can be applied consistently across a large and heterogeneous building stock. In Germany, the building codes of the federal states follow the Model Building Code (MBO), which formulates functional safety objectives and supplements them with prescriptive requirements for structural and organisational fire protection [1, 2]. For residential units on upper storeys, two independent rescue routes are generally required as a part of the system of means-of-egress. Depending on geometry and building configuration, these routes may involve protected corridors, internal or external protected stairways, external stairways, fire service rescue equipment, or safety stairways. Although the permitted configurations satisfy the same overarching regulatory objectives, the regulations do not assign a common explicit quantitative failure target to each configuration.

This situation is characteristic of prescriptive fire safety systems. Requirements encode accumulated technical experience, legal judgement, and accepted practice, while their residual risk is generally implicit rather than expressed as a numerical target [2, 3]. Consequently, two configurations that are both permissible under the same regulatory framework need not necessarily provide identical margins against loss of the egress function. Empirical incident data are indispensable for evaluating the performance of fire safety measures, but rare combinations of geometry, fire location, component state, and occupant behaviour make a direct statistical comparison of every regulatory configuration difficult. German fire service field assessments have provided a substantial empirical basis for evaluating building fire protection [4], and the underlying data collection has subsequently been expanded [5]; nevertheless, the sample size remains insufficient for direct stratification across all relevant combinations examined here.

The present study, therefore, addresses a comparative rather than an absolute risk question. The central hypothesis is that *prescriptively equivalent means-of-egress configurations can exhibit materially different relative safety levels within the same regulatory framework*. Fault tree analysis (FTA) is used as a transparent system model to test this hypothesis. The main contribution of this study is the systematic derivation and modelling of all relevant configurations within the selected regulatory framework. Unlike most previous applications, the analysis is not limited to a single building or fire scenario.

Three research questions are addressed: (i) how strongly do FTA-derived top-event scores differ among the identified configurations; (ii) which structural characteristics explain the principal differences; and (iii) is the relative ordering robust to plausible alternative numerical mappings of the expert judgement inputs? The analysis is deliberately not presented as a prediction of real-world annual failure probabilities. Instead, all configurations are evaluated with the same model logic and the same ex-ante input catalogue, allowing relative differences and implicit safety margins to be made explicit.

2 State of research and research gap

2.1 General principles of fault tree analysis

Fault tree analysis is a deductive, top-down method for analysing how combinations of component failures, human actions, external events, or other causal conditions can lead to a predefined undesired system state, referred to as the top event. The method originated in aerospace and missile-system safety in the early 1960s and was subsequently adopted in other safety-critical domains, particularly nuclear engineering, where it became an established element of probabilistic safety assessment [6–8]. FTA is internationally standardised and remains widely used for reliability and safety assessment of complex engineered systems [9].

The central principle of FTA is the hierarchical decomposition of the top event into intermediate and basic events connected by Boolean logic gates. In classical static fault trees, AND gates represent combinations for which all input events must occur, whereas OR gates represent combinations for which at least one input event is sufficient. This structure provides a qualitative representation of causal logic and, when probabilistic inputs are available, a quantitative calculation of the top-event probability. Qualitative evaluation can identify minimal cut sets, while quantitative evaluation can be extended to importance measures that describe the influence of individual basic events on the top event [7, 8].

FTA has been particularly influential in nuclear probabilistic safety assessment because it allows large technical systems to be decomposed into transparent and auditable failure paths and permits the effects of redundancy and safety functions to be evaluated [10]. In civil aerospace, FTA is likewise embedded in system safety assessment practice; SAE ARP4761A incorporates fault-tree reasoning within the safety assessment process for aircraft and airborne systems [11, 12]. NASA has formalised FTA for aerospace applications as a decision-support method for identifying design weaknesses and prioritising risk-reduction measures [6].

The principal strengths of classical FTA are transparent logic, traceability from system-level failure to underlying causes, and comparability of alternative system architectures. Its limitations are equally important: numerical results depend strongly on the input data and on assumptions concerning event dependence. Common-cause failures, repeated events, dependencies, and time-dependent interactions require explicit treatment and cannot generally be represented adequately by simple independent static basic events [13]. These characteristics make FTA suitable for the present comparative analysis, provided that the interpretation of the input values and the model boundaries is stated explicitly.

2.2 Fault-tree applications in fire safety and egress

FTA has been applied in fire-safety research, but existing studies mostly address individual systems or particular accident scenarios rather than a complete regulatory configuration space. Chen et al. [14] analysed causes and evacuation countermeasures for high-rise building fires, using a fire occurrence as the top event. Hu [15] applied FTA to hotel fire safety to identify causal factors and derive management measures.

Wang et al. [16] combined FTA with the analytic hierarchy process for fire-hazard assessment in a commercial complex, while Li et al. [17] coupled FTA with a dynamic Bayesian-network framework for subway fire risk.

Applications more directly related to egress are less common. Goodman [18] used FTA to assess the reliability of coal-mine escapeways and explicitly identified the limited availability of input probabilities as a constraint. Qiao et al. [19] linked a fault tree with agent-based evacuation modelling for subway stations, with failure to meet a target evacuation time as the top event. These studies show that FTA can represent interactions between building features and occupant behaviour. However, none of them systematically evaluates the full range of prescriptively permitted means-of-egress configurations.

More recently, Himoto [20] applied a probabilistic event-tree framework to assess building-to-building fire-spread performance against a statistically derived safety benchmark. Although focused on fire spread rather than egress, the study further illustrates the increasing adoption of event-logical risk assessment methods in fire-safety engineering.

2.3 Alternative quantitative approaches to egress safety

Probabilistic evacuation and performance-based methods provide complementary approaches. Chen and Mao [21] used Monte Carlo sampling to evaluate occupant-evacuation failure under uncertain factors. Zhang et al. [22] compared available safe egress time (ASET) with a probabilistic required safe egress time (RSET), combining fire modelling with Latin-hypercube sampling. Abolghasemzadeh [23] developed a BIM-integrated microscopic egress method that considers environmental conditions and occupant behaviour. Stan [24] compared regulatory egress requirements for assembly buildings using fire and evacuation simulations. The ALREKO research programme has examined enhanced-reliability stairways using probabilistic design fires and performance-based assessment [25].

Bayesian networks, event-tree frameworks, and other dependency-oriented probabilistic approaches can represent conditional relationships and complex dependencies more explicitly than classical fault trees. However, they generally require substantially greater model parameterisation and modelling effort. Since the objective of the present study is not to predict fire outcomes for a specific building but to compare a large set of prescriptively permitted means-of-egress configurations within a common analytical framework, FTA was selected as a transparent and traceable comparative modelling method.

These approaches can provide detailed physical or behavioural predictions, but they are comparatively resource intensive when the objective is to screen a large regulatory configuration space. The research gap addressed here is therefore not the absence of quantitative egress models as such. Rather, no study identified in the literature systematically derives the relevant prescriptive residential means-of-egress combinations from one regulatory framework and evaluates all of them with a common FTA structure and a common input catalogue to expose relative differences in implicit safety level.

3 Methodology

3.1 Configuration study and model set

The configuration study is based on the German MBO [1]. The German term *Rettungsweg* includes both self-evacuation routes and routes or provisions used for rescue by the fire service; the term "means-of-egress" is used here for readability, while the model retains the rescue function explicitly. Combinations were screened systematically using the sequence of horizontal and vertical route elements. Configurations that merely add requirements beyond the regulatory minimum were excluded because the objective is to compare minimum-compliant alternatives. Configurations that are geometrically possible but not permissible were also excluded. The complete screening logic and nomenclature are documented in Appendix A.1.

The final study comprises 21 models: fourteen represent standard MBO base configurations, plus two variants with a greater number of dwelling units connected to an egress element. Five additional models represent safety stairways or stairways with enhanced safety requirements. The latter includes an internal safety stairway modelled according to the Model High-Rise Guideline, external safety stair arrangements, and current state-specific enhanced-safety stair concepts [26–29].

3.2 Reference building and top event

The reference case is a multi-family residential building in German Building Class 5 with a ground floor and six upper storeys, while remaining below the regulatory high-rise threshold. The initiating fire is assumed to occur either within dwelling unit NE0 on the first upper storey, adjacent to the dwelling entrance door, or within the first escape-route element serving the dwelling. Dwelling unit NE0 is located in close proximity to the nearest vertical egress element. This arrangement intentionally represents a demanding scenario because the fire origin is located directly along a primary escape path, potentially affecting occupants from multiple storeys, while the location on the first upper storey maximises the number of dwelling units above the fire within the reference building geometry. The first upper storey was selected because the ground floor is not representative of the typical regulatory means-of-egress situation; owing to its location, it may provide additional egress options beyond those required by the applicable code. The total number of dwelling units varies between the analysed escape-route configurations.

The modelled top event is:

> **"Fire service rescue required outside dwelling unit** NE0 **prior to fire suppression."**

The exclusion of rescue operations within the dwelling unit NE0 is deliberate. Where the fire originates within NE0, occupants remaining inside the fire dwelling are excluded from the analysis. The objective of the study is instead to evaluate failure or severe impairment of the shared means-of-egress system and its consequences for other occupants. Consequently, for scenarios in which the fire originates within NE0, the top event represents situations in which occupants beyond dwelling unit NE0 require fire service assistance before fire suppression can be initiated. For scenarios in which the

fire originates within the first escape-route element, the focus remains on impairment of the shared egress system.

The top event is decomposed into three principal pathways: (i) fire spread via the first escape route element threatens occupants in another dwelling unit NE1 or NE2 (`GAusbreitNE`); (ii) an occupant becomes incapacitated in the first, generally horizontal, escape route element (`Gh1RWPers`); and (iii) an occupant becomes incapacitated in a subsequent vertical escape route element (`GvRWPers`). The full trees are provided in Appendix A.4.

3.3 Fault-tree logic and numerical calculation

The fault trees were implemented in R using the package `FaultTree` version 1.0.1 [30]. Static OR, AND, and inhibit gates are used. The scripts use the package's gate-by-gate calculation. For a set of numerical input values s_i, the score propagated through an AND gate is

$$S_{\mathrm{AND}} = \prod_{i=1}^{n} s_i, \tag{1}$$

and through an OR gate is

$$S_{\mathrm{OR}} = 1 - \prod_{i=1}^{n} (1 - s_i). \tag{2}$$

For the probability component of an inhibit gate, the two input values are multiplied. These equations correspond to conventional gate-by-gate FTA arithmetic under an independence assumption [7, 9]. In the present study, however, s_i is not generally an empirically calibrated probability. The resulting value is therefore denoted an *FTA-derived top-event score* rather than a failure probability.

The trees contain geometric, organisational/human, and technical basic events. Geometric factors include the number of dwelling units connected to a route element, corridor geometry, and the sequence of components of means-of-egress. Human and organisational events include inappropriate occupant behaviour, fear responses, malicious or negligent ignition, manipulation of safety components, and missing inspections. Technical events include failure or loss of effectiveness of door closers, doors and partitions, ventilation-related components, and other route-specific safety measures. In total, 93 distinct basic-event input values are defined in a common master catalogue (Appendix A.3).

3.4 Expert-judgement-based input model

The present model does not use empirically calibrated probabilities for the 93 basic events. All numerical inputs are expert-judgement values and were fixed *before* construction and evaluation of the 21 fault trees. This ex-ante procedure prevents subsequent adjustment of inputs to obtain a preferred ordering of configurations. The assessment was performed by the first author on the basis of professional expert judgement. The first author practises as a state-approved fire safety review engineer and serves as an examiner for candidates seeking the same professional qualification.

Expert judgement is a legitimate source of information when observational data are sparse, but its epistemic limitations and potential biases require explicit documentation [31, 32]. The present study therefore uses a deliberately simple, reproducible scale and reports the output only as a comparative score. Seven anchor levels are defined. Values 0 and 1 are excluded from the baseline assessment because no fire-safety event is assumed to be absolutely impossible or certain. The lower and upper anchors are 0.05 and 0.95, respectively, with 0.50 as the midpoint. Dividing each half interval into three equal increments produces

$$\mathcal{L} = [0.05,\ 0.20,\ 0.35,\ 0.50,\ 0.65,\ 0.80,\ 0.95]. \tag{3}$$

The seven values are numerical likelihood anchors used by the FTA arithmetic; they are not seven empirically calibrated probability classes. The fault trees include several alternative ignition pathways, such as accidental ignition, adverse occupant behaviour, malicious ignition, and technical failure. The associated numerical values are assigned as relative expert-judgement scores within the comparative model and are not interpreted as empirically calibrated occurrence probabilities. Because fire occurrence is a precondition of the analysed scenario, ignition-location scores are interpreted as relative pathway weights conditional on a fire occurring. Five inputs use deliberately assigned special expert-judgement values when the anchor scale was considered too coarse: `PBraABewohn` and `PmaniFTS` use 0.15, `PDefektRed` and `PStromfehlSSV` use 0.025, and `PvRWPers` uses 0.0001. None is assigned exactly 0 or 1.

Each input additionally carries metadata describing internal confidence (`qual`), time dependence (`zeitab`), and potential influenceability (`beein`). Currently, all inputs are assigned to confidence class 1 because their values are derived exclusively from expert judgement. Future model updates may incorporate additional confidence classes as empirical observations, measurements, or other evidence-based data become available. These metadata do not modify the calculation in the present study; they document epistemic quality and support future model refinement. All 93 values are expert-judgement inputs; no source code is interpreted as an empirical provenance category in this article.

3.5 Worked example: `nFl_0_iTR_FW`

The configuration `nFl_0_iTR_FW` is used as a worked example. It consists of a protected corridor as the first element of horizontal egress, an internal protected stairway as one vertical route, and fire service rescue as the second route. Figure 1 shows the corresponding type floor plan; Figure 2 shows the top event and its three principal branches. The complete tree is reproduced in Figure 28.

For this configuration, impairment of the first horizontal egress route has a score of $S = 0.754207$. The two branches representing threatened burn-through to neighbouring dwelling units (NE1 and NE2) are inhibit combinations of this route impairment with door scores 0.50 and 0.35, resulting in 0.377104 and 0.263973. Their OR combination gives

$$S_{\texttt{GAusbreitNE}} = 1 - (1 - 0.377104)(1 - 0.263973) = 0.541531. \tag{4}$$

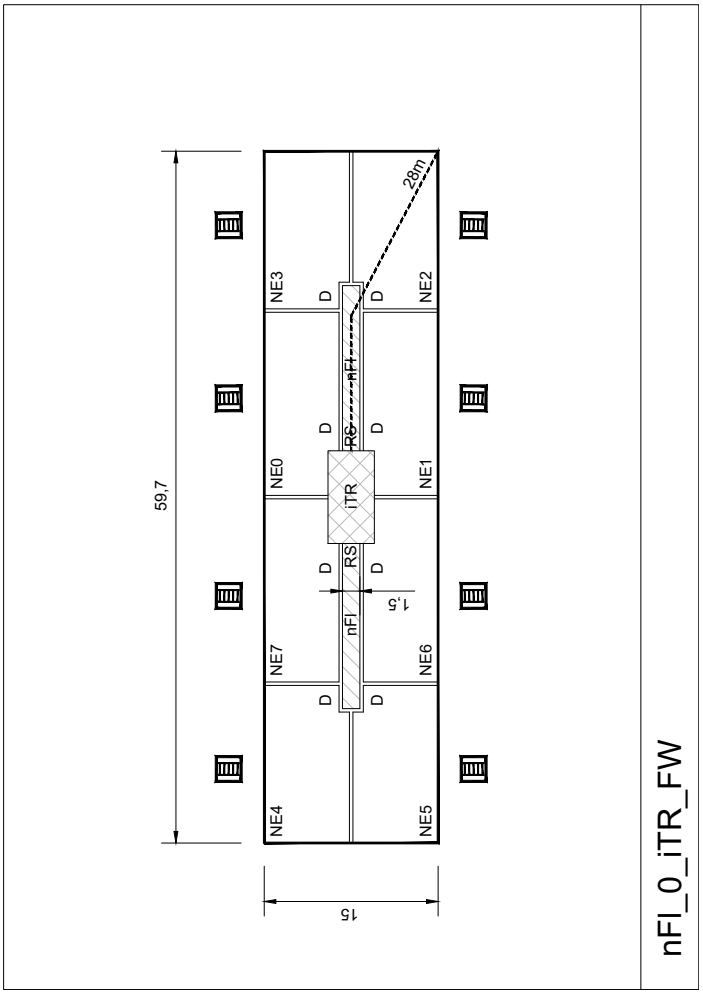


Fig. 1 Type floor plan of the worked example `nFl_0_iTR_FW`.

For occupant incapacitation in the horizontal element, the score for occupants using the compromised route is 0.737856; the score for route impairment with threshold exceedance is 0.701413. Their AND combination gives

$$S_{\texttt{Gh1RWPers}} = 0.737856 \times 0.701413 = 0.517542. \tag{5}$$

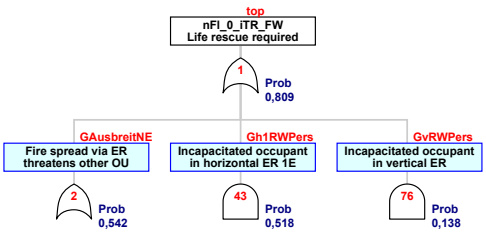


Fig. 2 Top event and the three principal intermediate-event branches used in the FTA.

The corresponding vertical-route branch is

$$S_{\texttt{GvRWPers}} = 0.422400 \times 0.327854 = 0.138486. \tag{6}$$

Finally, the three principal branches are connected by an OR gate:

$$S_T = 1 - (1 - 0.541531)(1 - 0.517542)(1 - 0.138486) = 0.809440. \tag{7}$$

This calculation illustrates why the numerical output is useful for internally consistent comparison while not being interpreted as an empirical probability of rescue demand.

3.6 Robustness and importance analyses

Two complementary sensitivity analyses are used. First, the dependence of the 21-scenario ranking on the numerical spacing of the expert scale is tested using a monotonic logit transformation applied to *all* 93 numerical inputs, including the five special values:

$$\operatorname{logit}(s_i^{(k)}) = k \operatorname{logit}(s_i). \tag{8}$$

The baseline corresponds to $k = 1$. A compressed mapping ($k = 0.75$) moves values towards 0.5, whereas an expanded mapping ($k = 1.25$) moves them away from 0.5 while preserving order, the midpoint, and the open interval $(0, 1)$. The transformed seven anchor values are listed in Table 1. Rank stability is evaluated using Spearman's ρ and Kendall's τ for all 21 models and separately for the 16 standard-code configurations.

Table 1 Baseline and alternative monotonic mappings of the seven expert-judgement-anchors.

Level	Baseline ($k = 1$)	Compressed ($k = 0.75$)	Expanded ($k = 1.25$)
1	0.05	0.099	0.025
2	0.20	0.261	0.150
3	0.35	0.386	0.316
4	0.50	0.500	0.500
5	0.65	0.614	0.684
6	0.80	0.739	0.850
7	0.95	0.901	0.975

Second, RAW/RRW-style local importance ratios are calculated for the worked example. Because the study output is a score rather than a calibrated risk probability, these are explicitly interpreted as diagnostic score ratios:

$$\mathrm{RAW}_i^S = \frac{S_T(E_i = 1)}{S_T}, \qquad \mathrm{RRW}_i^S = \frac{S_T}{S_T(E_i = 0)}. \tag{9}$$

The values 0 and 1 are used only in these counterfactual importance calculations and are not baseline expert assignments. The ratios identify events to which the worked-example score is locally most sensitive [33].

4 Results

4.1 FTA-derived scores across the 21 configurations

Table 2 reports the FTA-derived top-event scores for all 21 configurations. Figure 3 provides the same results in ascending order. Across the 19 non-variant configurations, the lowest score is 0.274 for `nFl_VoR_iSiTR_0` and the highest is 0.809 for `nFl_0_iTR_FW`, corresponding to a comparative score ratio of 2.95. The value of the variation configuration with smaller dwellings `nFl_0_iTR_FW_75` is 0.852.

The central regulatory comparison concerns the 14 standard MBO base configurations, excluding the five safety stair and enhanced safety stairway concepts. Within this group, the scores range from 0.477 for `oG_0_AT_AT` to 0.809 for `nFl_0_iTR_FW`. The comparative score ratio is 1.70. When the two variation configurations (`nFl_0_iTR_FW_75` and `nFl_0_iTR_iTR_75`) are also included in the comparison of the 16 standard-code configurations, the resulting values range from 0.477 to 0.852 for `nFl_0_iTR_FW_75`, corresponding to a comparative score ratio of 1.79.

Thus, even after excluding configurations that are explicitly designed to provide enhanced protection, prescriptively admissible standard arrangements do not collapse to a common comparative score.

Table 2 FTA-derived top-event scores for all investigated configurations, sorted in ascending order. The relative index is normalised to the lowest score among all 21 configurations.

Scenario	Top-event score [-]	Relative index [-]
nFl_VoR_iSiTR_0	0.274	100.000
nFl_0_iTRerSi1_0	0.303	110.479
nFl_oGfL_aSiTR_0	0.305	111.157
oG_0_AT_AT	0.477	173.963
oG_0_AT_aTR	0.482	175.711
oG_oGfL_aSiTR_0	0.506	184.316
oG_0_AT_FW	0.513	186.753
oG_0_aTR_AT	0.532	193.975
oG_0_aTR_aTR	0.535	194.986
oG_0_AT_FW_V1	0.549	200.081
oG_0_aTR_FW	0.593	215.957
0_0_iTR_FW	0.630	229.432
nFl_0_iTRerSi2_0	0.677	246.662
nFl_0_AT_AT	0.743	270.876
nFl_0_AT_iTR	0.743	270.876
nFl_0_iTR_iTR	0.766	279.133
nFl_0_iTR_AT	0.766	279.133
nFl_0_iTR_iTR_75	0.790	287.980
nFl_0_AT_FW	0.791	288.229
nFl_0_iTR_FW	0.809	294.954
nFl_0_iTR_FW_75	0.852	310.578

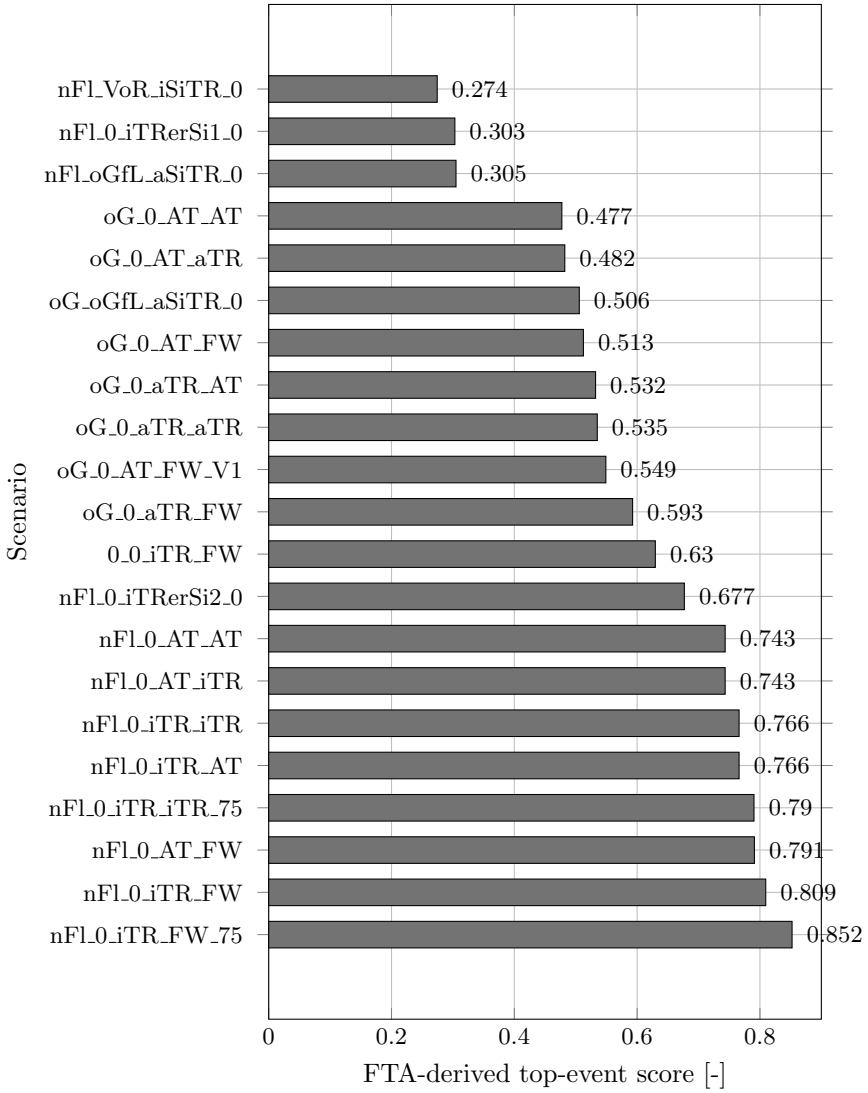


Fig. 3 FTA-derived top-event scores for all 21 configurations. Values are comparative model scores and must not be interpreted as observed failure probabilities.

4.2 Structural patterns in the results

The ordering exhibits several consistent structural patterns. Configurations with a protected corridor and only one direction towards a vertical route, combined with fire service rescue, are among the highest-scoring standard cases. `nFl_0_AT_FW` and `nFl_0_iTR_FW` yield scores of 0.791 and 0.809, respectively. Increasing the number of dwelling units connected to the first egress element raises the score further: `nFl_0_iTR_FW_75` reaches 0.852. This increase originates mainly from the greater number of occupant-use pathways represented in the horizontal route branch.

Protected corridor arrangements with two directional alternatives show moderately lower scores. The combinations `nFl_0_AT_AT`, `nFl_0_AT_iTR`, `nFl_0_iTR_AT`, and `nFl_0_iTR_iTR` lie between 0.743 and 0.766. Open-gallery configurations with two vertical alternatives form the lower part of the standard-code range, including `oG_0_AT_AT` (0.477) and `oG_0_AT_aTR` (0.482). The model therefore captures the expected benefit of alternative egress directions and route elements exposed to the external atmosphere, while quantifying the magnitude of this benefit within a single consistent framework.

The lowest scores occur for the more strongly protected safety stairway concepts. `nFl_VoR_iSiTR_0`, which contains the most extensive separation and system measures among the investigated configurations, yields 0.274. The enhanced-safety stair model `nFl_0_iTRerSi1_0` and the external safety stair configuration `nFl_oGfL_aSiTR_0` yield similarly low scores of 0.303 and 0.305. By contrast, `nFl_0_iTRerSi2_0` scores 0.677. These results are comparative model outputs; they do not constitute a regulatory compliance judgement on any specific state-level concept.

4.3 Robustness to the numerical scale

The relative ordering is highly stable under the two alternative monotonic mappings. For all 21 models, the compressed transformation ($k = 0.75$) gives Spearman $\rho = 0.986$ and Kendall $\tau = 0.952$ relative to the baseline ranking. The expanded transformation ($k = 1.25$) gives $\rho = 0.999$ and $\tau = 0.990$. For the 16 standard-code configurations alone, the corresponding coefficients are $\rho = 0.971/\tau = 0.932$ and $\rho = 0.997/\tau = 0.983$. Thus, moderate compression or expansion of the numerical spacing changes some neighbouring positions but does not materially overturn the overall ordering.

Table 3 Rank stability of the top-event score under alternative monotonic mappings of all basic-event inputs.

Comparison with baseline	Spearman ρ	Kendall τ
Compressed mapping, all 21 models	0.986	0.952
Expanded mapping, all 21 models	0.999	0.990
Compressed mapping, 16 standard models	0.971	0.932
Expanded mapping, 16 standard models	0.997	0.983

4.4 Local importance in the worked example

Table 4 lists the ten largest RAW/RRW-style importance ratios in the worked example. The largest RRW-style value is associated with fire ignition in the reference fire dwelling because the analysed top event is conditional on the modelled critical residential fire pathway. Door performance, occupant behaviour, and impairment of the protected corridor also appear among the most influential inputs. This confirms that the model is sensitive not only to structural separation but also to human and operational pathways.

Table 4 Largest local score-importance ratios for the worked example `nFl_0_iTR_FW`.

Basic event	Short description	Baseline	RAW^S	RRW^S
`PBraANE0`	Fire ignition in NE0	0.800	1.096	5.049
`PTDNE1nFlFW`	D nFl_FW D NE1 br	0.500	1.143	1.166
`PTDNE2nFlFW`	D nFl_FW D NE2 br	0.350	1.157	1.092
`PFehlverhNEx`	Occu. misconduct NEx	0.200	1.122	1.143
`PBraStift`	Malicious arson	0.050	1.133	1.009
`PTDzerst`	Door NE0 D burn	0.650	1.042	1.103
`PAngstNERW1`	Occu. fear response	0.200	1.090	1.094
`PRauchnFlFWP`	Smokecon. nFl_FW ¿ TH	0.800	1.019	1.082
`PAngstNERW2`	Occu. fear response	0.050	1.052	1.006
`PAngstNE0`	Occu. fear response	0.500	1.042	1.050

5 Discussion

5.1 Implicit safety differences within a prescriptive framework

The main finding supports the study hypothesis: configurations that are admissible as standard solutions under the same prescriptive framework can produce substantially different comparative safety scores. The result is most clearly demonstrated by the standard-code subset, for which the highest top-event score is associated with a comparative score ratio of 1.70 relative to the lowest-scoring configuration. Because the same top event, basic-event catalogue, and assessment logic are applied to every configuration, this difference arises from the structure and requirements of the distinct system of means-of-egress rather than from scenario-specific recalibration.

The finding should not be interpreted as evidence that the MBO is unsafe or that any individual compliant configuration fails to meet an acceptable absolute risk target. No such target is estimated in this study. The analysis shows that configurations regarded as equivalent under the prescriptive code framework do not necessarily perform equally when their underlying failure pathways are examined using a common fault-tree structure. This distinction is important for future performance-based or risk-informed regulation because it identifies where safety margins may be comparatively larger or smaller without assigning an absolute acceptability threshold.

5.2 Drivers of the relative differences

The model structure explains the principal trends. A greater number of dwelling units connected to the affected element of means-of-egress creates more occupant-use pathways and therefore raises the score when the individual input assumptions are held constant. Two-directional route configurations benefit from an alternative path away from the fire-affected location. Lower scores are also associated with configurations requiring self-closing or fire-rated doors between the fire compartment and the adjoining means-of-egress element, as these barriers interrupt several fire and smoke propagation pathways. Open-gallery configurations and externally located stairways reduce the likelihood of critical smoke and heat conditions in means-of-egress compared with enclosed internal egress elements. Safety stairway concepts introduce stronger separation, vestibules, smoke-control functions, or other barriers that interrupt causal sequences.

The worked example also illustrates the interaction between structural and behavioural factors. The horizontal-route branch combines route impairment and threshold exceedance with the numerical expert input representing occupants' continued use of the compromised route. Consequently, the comparative assessment cannot be reduced to component reliability alone. This is consistent with the broader fire-safety literature, which recognises that evacuation performance depends on both environmental conditions and human response [22, 23].

5.3 Implications for regulatory analysis

The method can support regulatory analysis in three ways. First, proposed changes to prescriptive requirements can be represented explicitly in the fault tree and compared with an existing standard configuration before implementation. Second, deviations in individual building projects can be screened against a reference configuration using a common causal model. Third, the method can identify which requirements or basic events dominate the relative score and therefore warrant higher-quality empirical data or targeted engineering analysis.

These uses are decision-support applications rather than automatic approval criteria. In particular, the present scores do not justify reducing a requirement simply because one configuration shows a lower score than another. A regulatory decision would additionally require calibrated consequence measures, uncertainty treatment, legal safety objectives, and evidence that the model captures the relevant physical and behavioural mechanisms. The FTA should therefore be viewed as a transparent comparative layer that can complement more detailed fire and evacuation simulations, experimental evidence, and incident statistics.

5.4 Robustness, uncertainty, and limitations

The strongest limitation is the input model. All 93 numerical inputs are based on a single expert assessment, albeit one performed by an experienced and formally qualified fire-safety professional and fixed before model construction. A different expert could

assign different numerical scores. The robustness analysis therefore evaluates sensitivity to the numerical mapping of the assigned values, but not variability between experts.

The seven-level anchors and the five special values impose numerical structure on judgements that are fundamentally epistemic. In particular, multiplication and complementation in gate-by-gate FTA arithmetic assume ratio-scale meaning that is stronger than a purely ordinal judgement. For this reason, the outputs are deliberately reported as scores rather than probabilities. Formal multi-expert elicitation, calibration questions, or empirical estimation would strengthen future versions of the model [31, 32].

The monotonic transformation analysis indicates that the overall ranking remains highly stable even when the spacing of the expert-judgement scale is compressed or expanded. It does not establish that the baseline values are correct, nor does it quantify full epistemic uncertainty. The local RAW/RRW-style analysis likewise identifies influential assumptions but cannot substitute for calibration.

Both the present FTA framework and the event-tree approach proposed in [20] rely on propagating uncertain input parameters through an explicit event-logical model. However, whereas Himoto derives parameter distributions from fire statistics and probabilistic engineering models, the present study currently relies on expert-based scores. Consequently, uncertainty in the present model primarily originates from expert judgement, whereas Himoto's framework explicitly incorporates statistical and physical uncertainty.

A second limitation concerns statistical dependence. The implementation uses static gate-by-gate calculations. Repeated or causally related events can therefore create dependencies that are not fully represented by simple independent-event arithmetic. Some repeated branches in the scripts are used as reusable instances of the same parameterisation, while other pathways can share physical causes. The present comparison applies this convention consistently to all models, but the resulting scores should not be interpreted as absolute system probabilities. A future model version should explicitly distinguish independent repeated instances, common-cause events, and shared physical events and compare gate-by-gate results with dependency-aware methods such as binary decision diagrams or Bayesian networks [8, 13].

Third, the study is restricted to a residential building-class-5 reference geometry and one demanding fire location. Variations in floor level, dwelling layout, occupant demographics, fire growth, door-opening sequences, and fire service intervention can change the causal structure or input values. The model therefore establishes a comparative framework and a specific case-study result, not a universal ranking for all residential buildings.

5.5 Transferability and future work

The framework can be extended to other occupancies, special-building regulations, existing buildings, and international code comparisons. The most important next step is empirical calibration. As fire service incident datasets grow, selected basic-event inputs can be replaced by observed frequencies or distributions. Full-scale tests and fire

simulations can be used to quantify door failure, smoke spread, and tenability thresholds, while evacuation models can refine occupant-use pathways. This would permit a gradual transition from comparative expert-judgement scores towards probabilistically calibrated system models.

The approach is also suitable for testing targeted regulatory modifications. Enhanced-safety stair concepts are a current example: rather than treating a regulatory variant as simply equivalent or non-equivalent to a benchmark, the FTA can reveal which causal pathways are strengthened and which remain dominant. Such results can then guide focused experiments or simulations before regulatory conclusions are drawn.

6 Conclusions

A systematic set of 21 residential means-of-egress configurations was derived from German prescriptive requirements and evaluated using a common fault-tree framework. The study leads to five main conclusions:

1. Prescriptive admissibility does not imply identical comparative safety performance. Within the 14 standard-code configurations, the FTA-derived top-event score varies from 0.477 to 0.809, a comparative score ratio of 1.70.
2. Route topology matters. Alternative directions, open-air route elements, stronger separation, and safety stair features interrupt different causal pathways and systematically affect the comparative score.
3. The principal ordering is robust to moderate monotonic compression and expansion of the expert-judgement scale, with rank correlations remaining high for both the full model set and the standard-code subset.
4. The numerical outputs are comparative FTA-derived scores, not empirically validated probabilities. Their interpretation must remain relative until the basic-event inputs are calibrated with data or formal elicitation.
5. The framework can be used to compare implicit safety margins and evaluate potential regulatory changes. However, it is not a substitute for detailed physical modelling, empirical evidence, or regulatory judgement.

Data availability

The complete configuration study, type floor plans, all 93 basic-event input values, and the 21 complete fault-tree diagrams are documented in the digital Appendix included in this manuscript. The R scripts and the master input file used for the calculations are available from the corresponding author on reasonable request.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used OpenAI ChatGPT to support manuscript structuring, language editing, consistency checking, and computational

cross-checking. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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A Complete model documentation

This digital Appendix forms part of the same manuscript document. It contains the complete configuration study, all type floor plans used for the 21 analysed models, the full table of 93 basic-event input values, and the complete fault-tree diagrams.

A.1 Combination study

The screening starts from the route components permitted by the MBO and identifies minimum-compliant combinations without adding measures that would intentionally exceed the minimum regulatory requirement. The original combination matrix also screens fire origin and the applicability of individual route components. Its selection codes are summarised in Table 5. Configurations that exceed the minimum requirements or are not permissible are not retained as standard models. Fire origins in a second route element are not represented as separate models where, under the defined top-event logic, they do not generate an additional relevant pathway.

The nomenclature is: `nFl` = protected corridor; `oG` = open gallery; `oGfL` = open gallery in free airflow; `VoR` = vestibule; `iTR` = internal protected stairway; `aTR` = externally accessed protected stairway; `AT` = external stair; `FW` = rescue by fire service; `iSiTR` and `aSiTR` = internal and external safety stairway; `iTRerSi1` and `iTRerSi2` = the two enhanced-safety stairway concepts considered. Safety stairways are represented according to the MHHR where no more general configuration rule is available; the state-specific enhanced-safety concepts are included as explicit comparison cases. The suffixes `V1` and `75` identify dwelling-density variations and do not introduce a new route topology.

Table 5 Selection codes used in the underlying combination study.

Code	Meaning in the screening matrix
0	Combination not applicable or not geometrically possible
1	Combination applicable and retained as relevant
2	Combination possible but exceeding the regulatory minimum
3	Combination possible but not permissible under the applied rules
X	Applicable condition not retained as a separate top-event pathway
1*	Asymmetric alternative requiring evaluation of both relative placements

The 21 configurations retained for analysis are listed in Table 6. The complete combination study is given in Figure 4.

Table 6: Systematic model set retained from the combination study. H1/H2 denote horizontal route elements and V1/V2 vertical/means-of-egress elements.

Scenario	H1	H2	V1	V2	Classification
0_0_iTR_FW	-	-	iTR	FW	MBO standard
nFl_0_iTR_FW	nFl	-	iTR	FW	MBO standard
nFl_0_AT_FW	nFl	-	AT	FW	MBO standard
nFl_oGfL_aSiTR_0	nFl	oGfL	aSiTR	-	Safety stair
nFl_0_iTR_iTR	nFl	-	iTR	iTR	MBO standard
nFl_0_AT_AT	nFl	-	AT	AT	MBO standard
nFl_0_iTR_AT	nFl	-	iTR	AT	MBO standard
nFl_0_AT_iTR	nFl	-	AT	iTR	MBO standard
oG_0_aTR_FW	oG	-	aTR	FW	MBO standard
oG_0_AT_FW	oG	-	AT	FW	MBO standard
oG_oGfL_aSiTR_0	oG	oGfL	aSiTR	-	Safety stair
oG_0_aTR_aTR	oG	-	aTR	aTR	MBO standard
oG_0_AT_AT	oG	-	AT	AT	MBO standard
oG_0_aTR_AT	oG	-	aTR	AT	MBO standard
oG_0_AT_aTR	oG	-	AT	aTR	MBO standard
nFl_0_iTRerSi1_0	nFl	-	iTRerSi1	-	Enhanced-safety stair
nFl_0_iTRerSi2_0	nFl	-	iTRerSi2	-	Enhanced-safety stair
nFl_VoR_iSiTR_0	nFl	VoR	iSiTR	-	Safety stair
oG_0_AT_FW_V1	oG	-	AT	FW	MBO standard; density variant
nFl_0_iTR_iTR_75	nFl	-	iTR	iTR	MBO standard; 75 m^2 variant
nFl_0_iTR_FW_75	nFl	-	iTR	FW	MBO standard; 75 m^2 variant

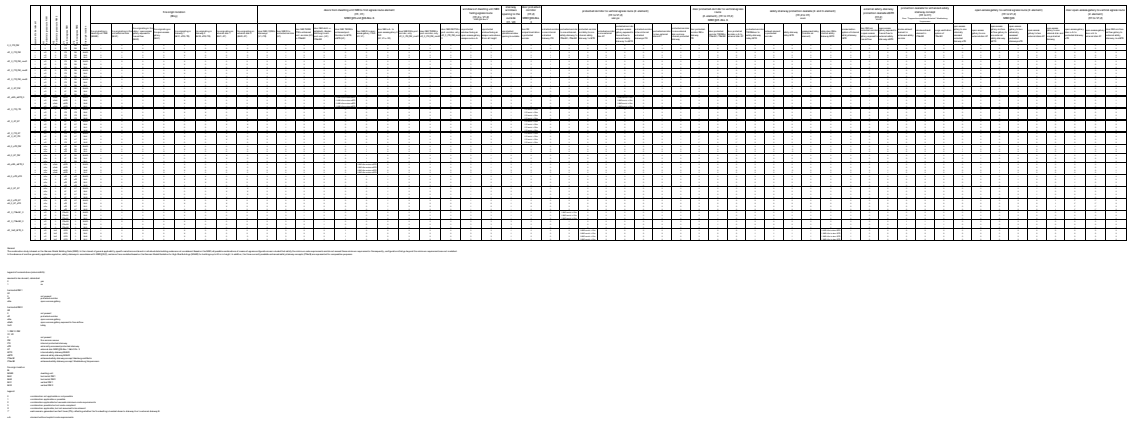


Fig. 4 Complete means-of-egress combination study.

A.2 Type floor plans

The following drawings document the geometrical configurations used to construct the 21 fault trees. Figure 26 illustrates that two modelled systems can occur in one building; it is included for interpretation only and is not a 22nd model.

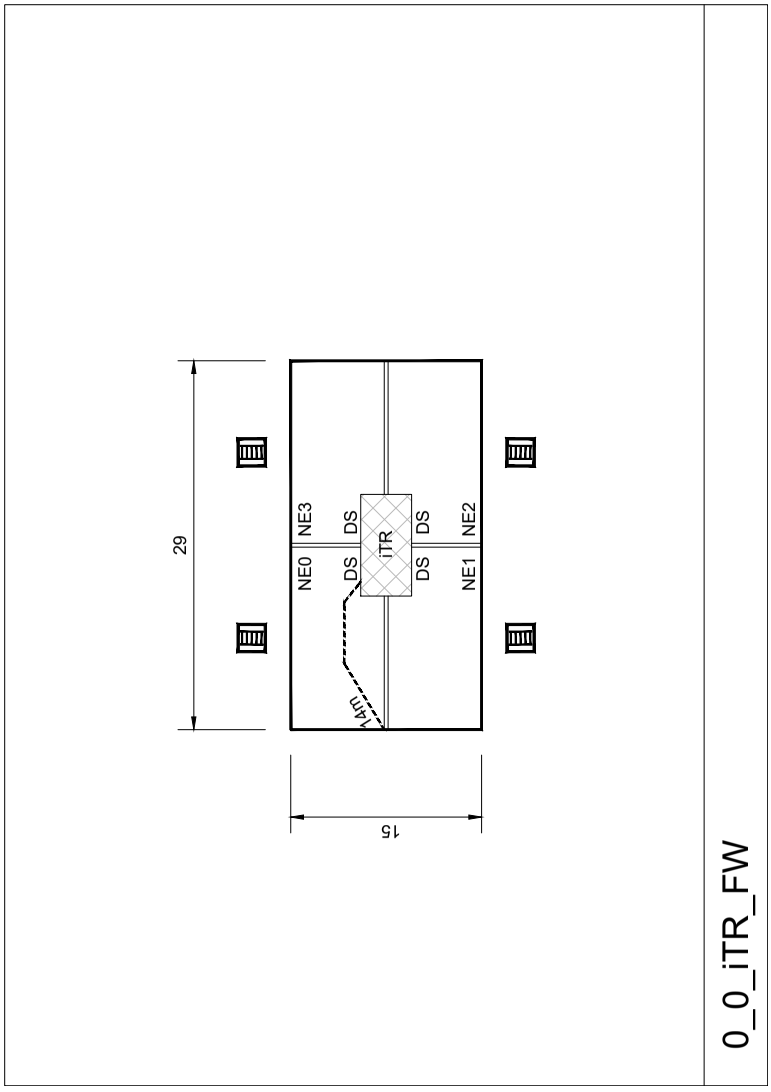


Fig. 5 Type floor plan for `0_0_iTR_FW`.

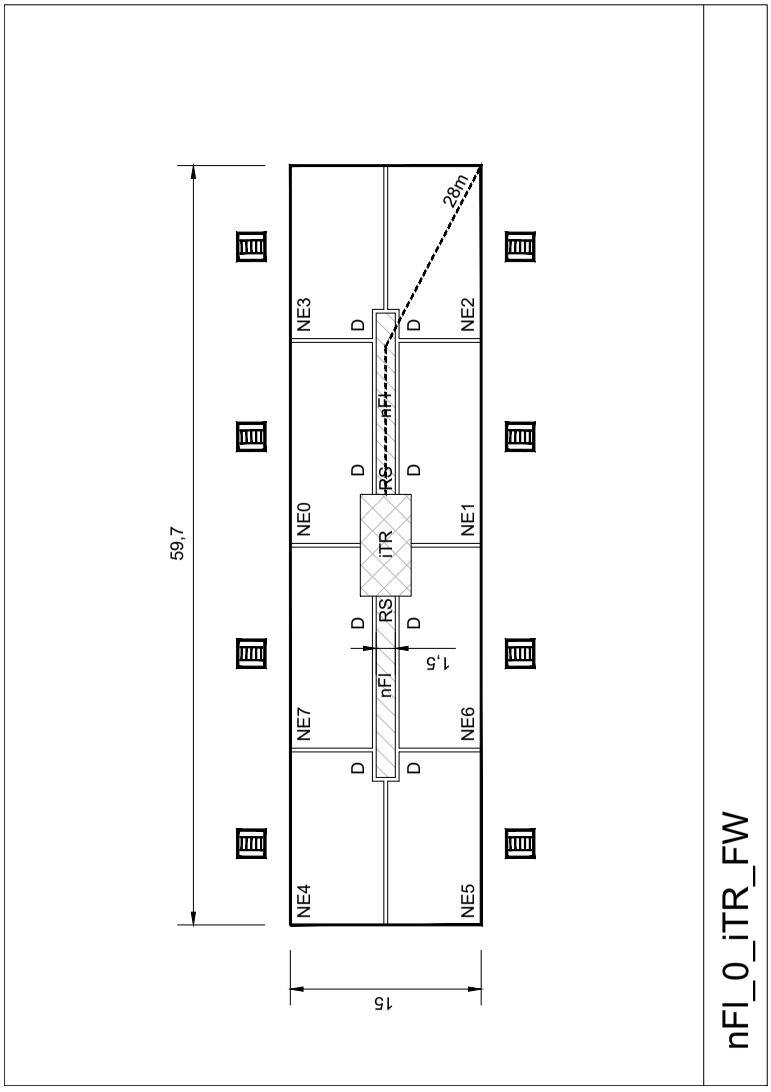


Fig. 6 Type floor plan for `nFl_0_iTR_FW`.

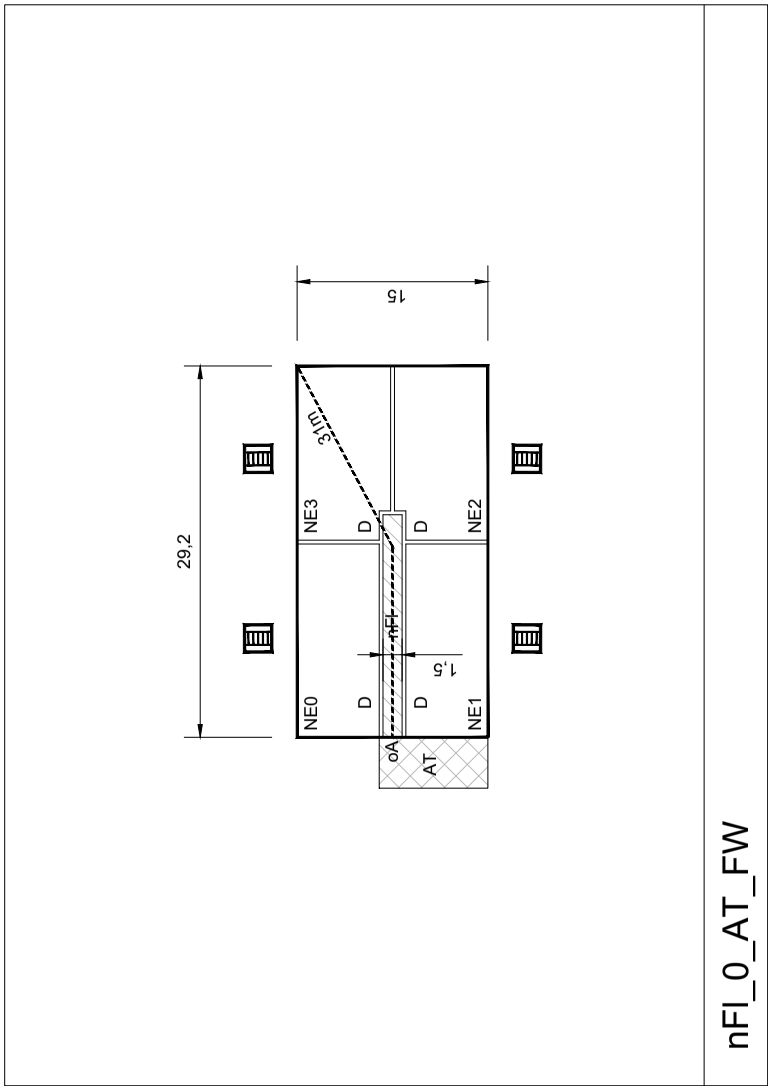


Fig. 7 Type floor plan for `nFl_0_AT_FW`.

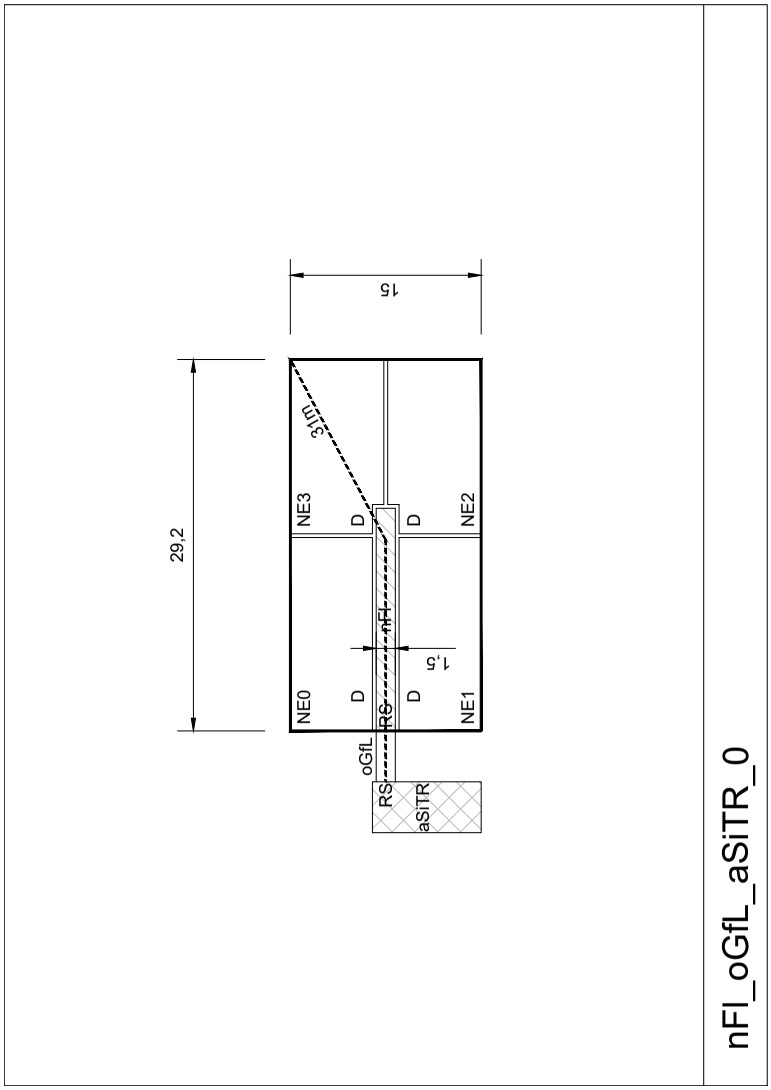


Fig. 8 Type floor plan for `nFl_oGfL_aSiTR_0`.

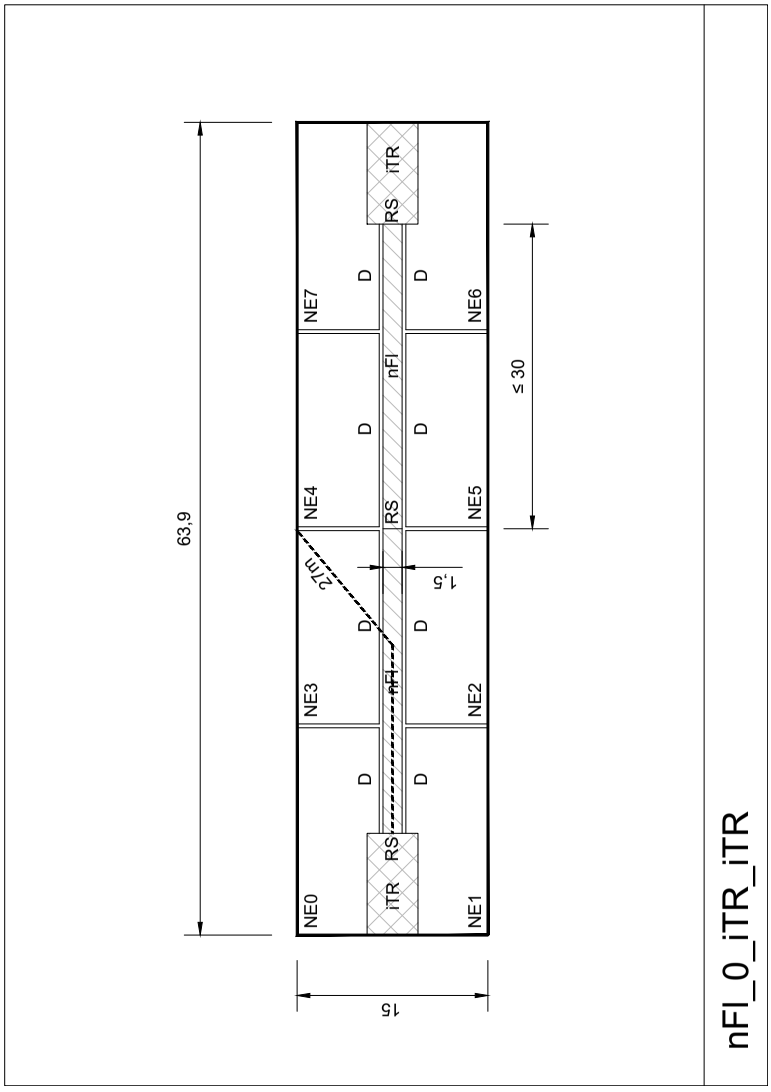


Fig. 9 Type floor plan for `nFl_0_iTR_iTR`.

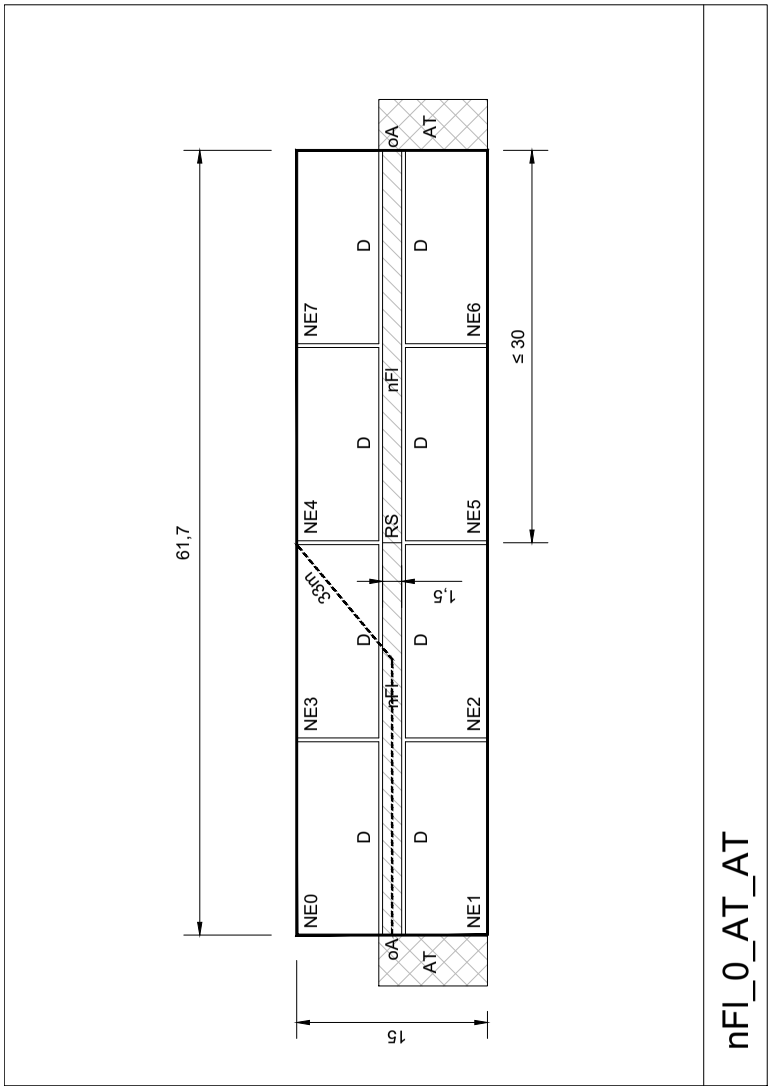


Fig. 10 Type floor plan for `nFl_0_AT_AT`.

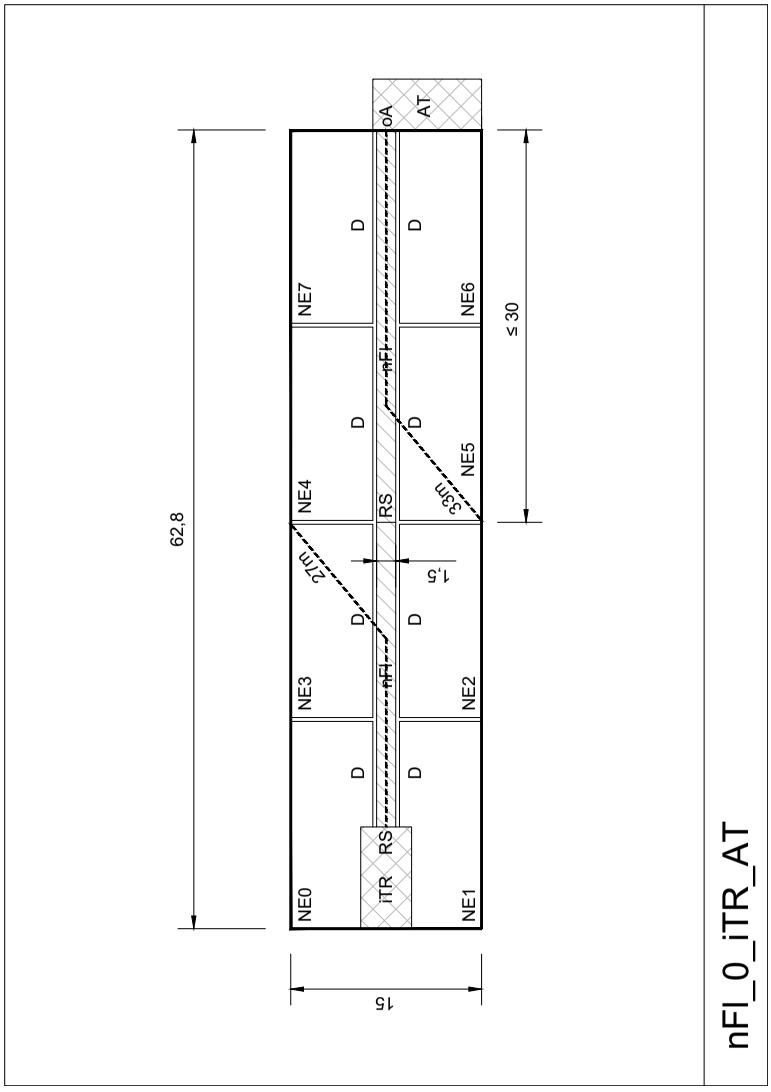


Fig. 11 Type floor plan for `nFl_0_iTR_AT`.

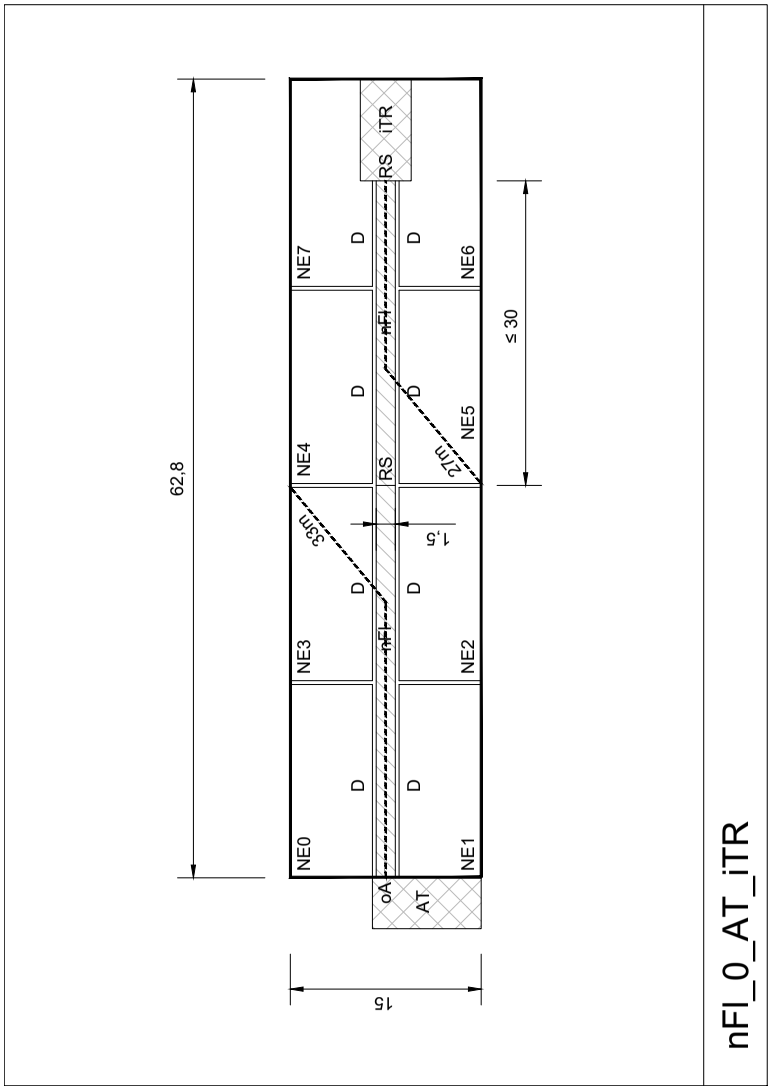


Fig. 12 Type floor plan for `nFl_0_AT_iTR`.

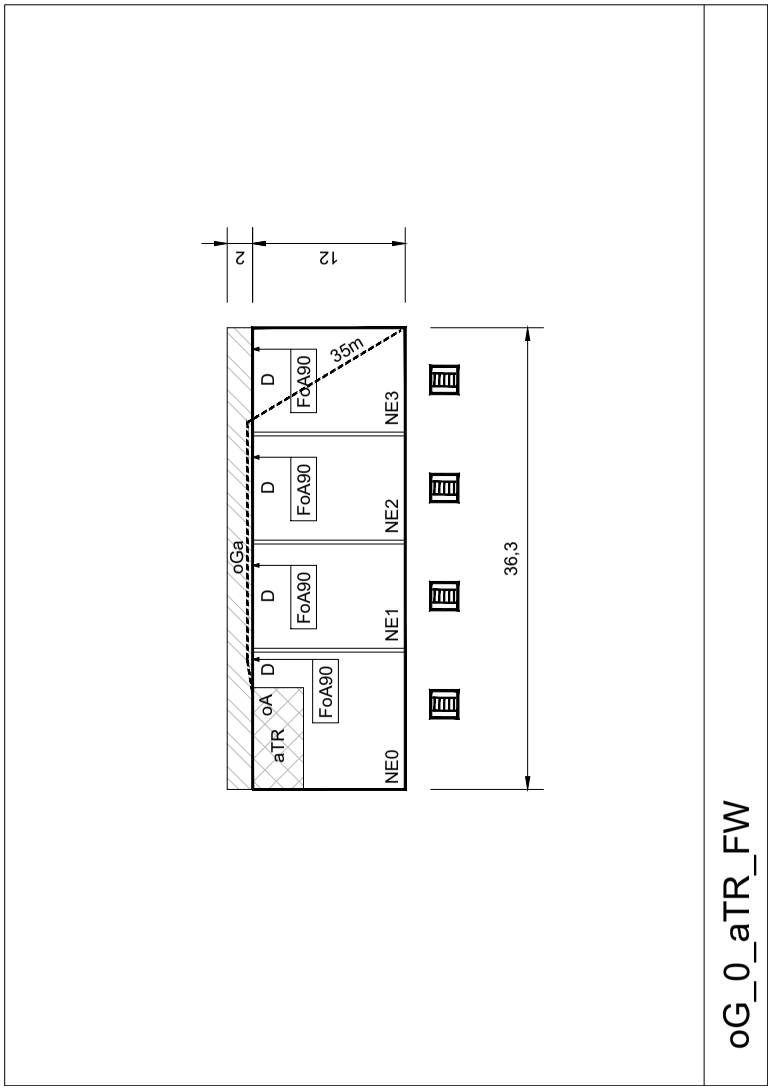


Fig. 13 Type floor plan for `oG_0_aTR_FW`.

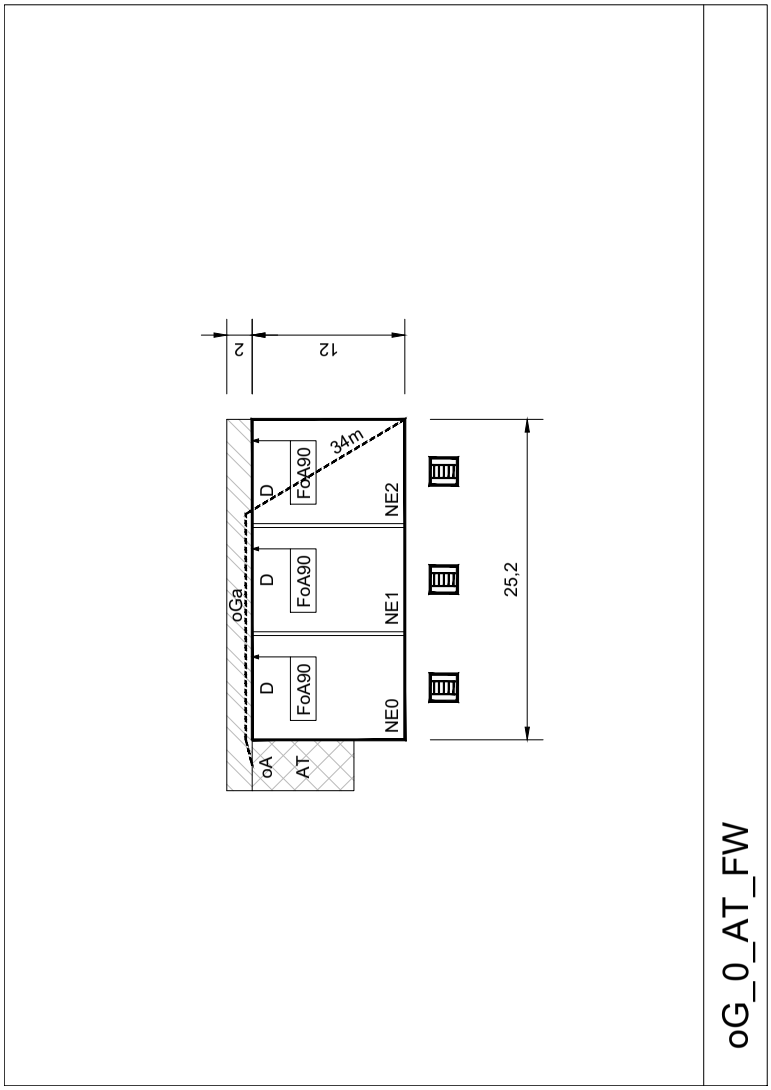


Fig. 14 Type floor plan for `oG_0_AT_FW`.

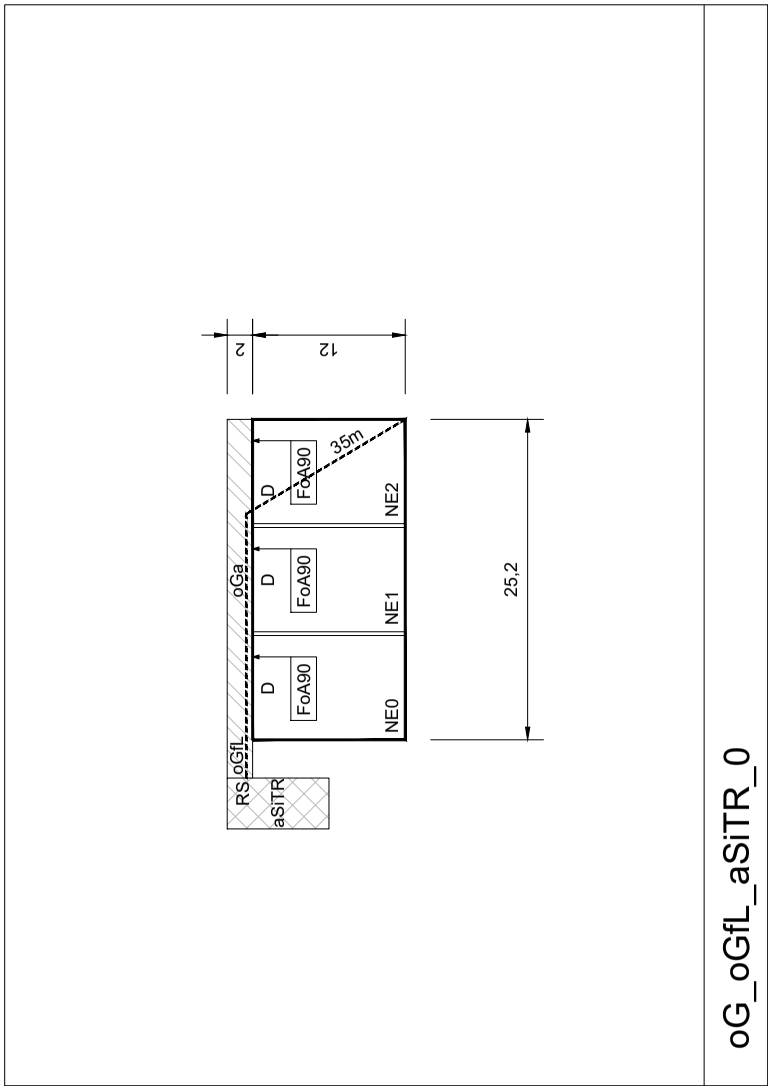


Fig. 15 Type floor plan for `oG_oGfL_aSiTR_0`.

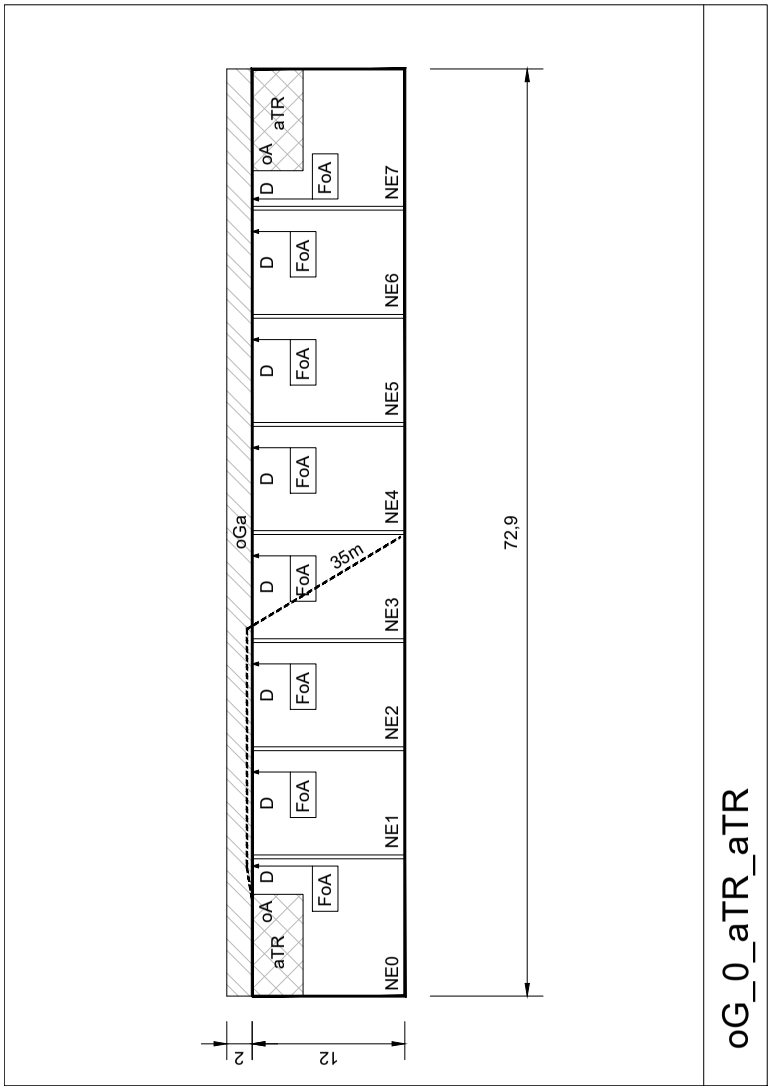


Fig. 16 Type floor plan for `oG_0_aTR_aTR`.

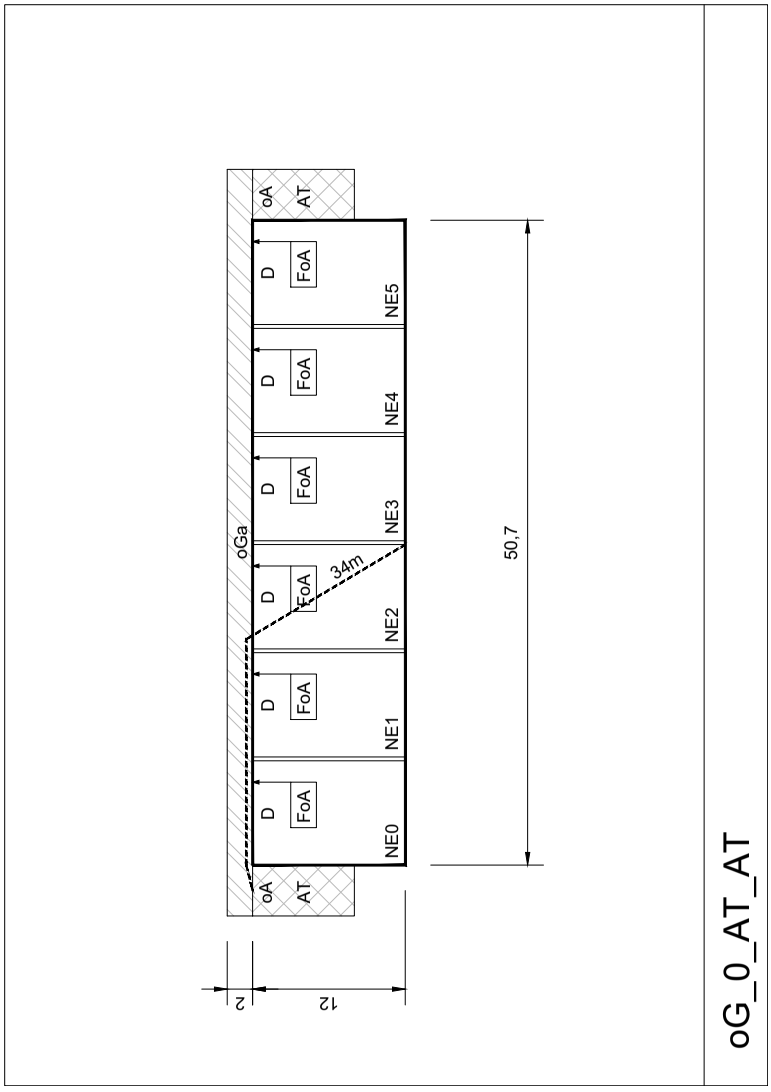


Fig. 17 Type floor plan for `oG_0_AT_AT`.

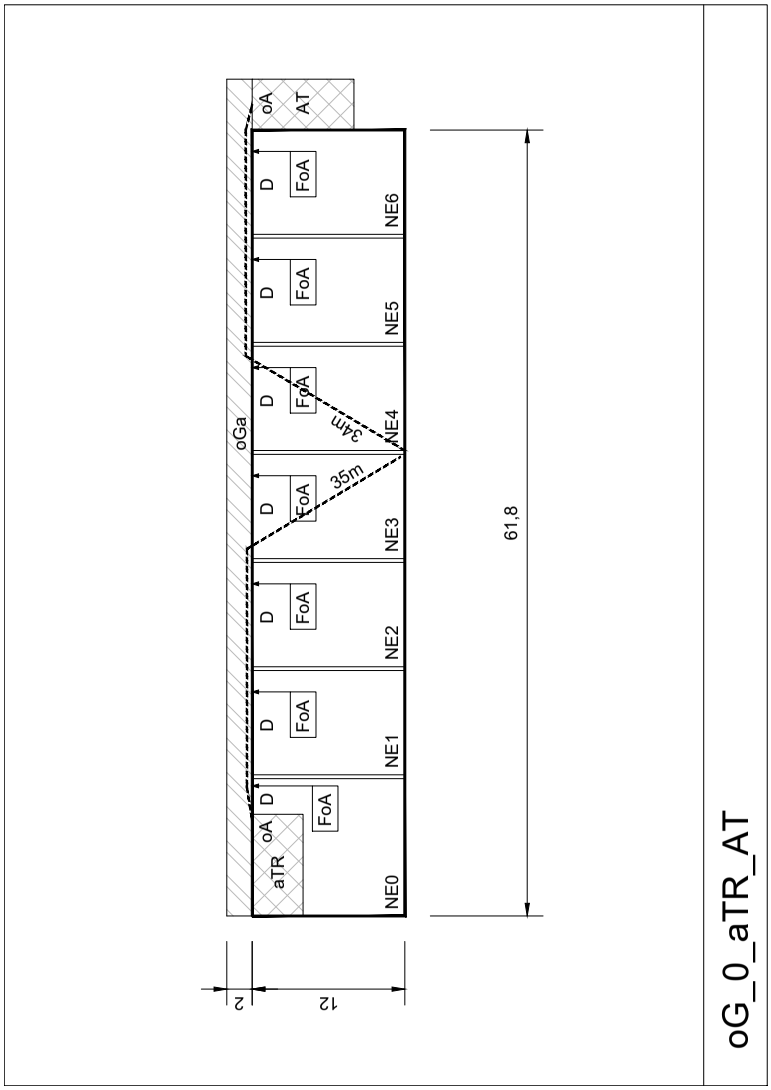


Fig. 18 Type floor plan for `oG_0_aTR_AT`.

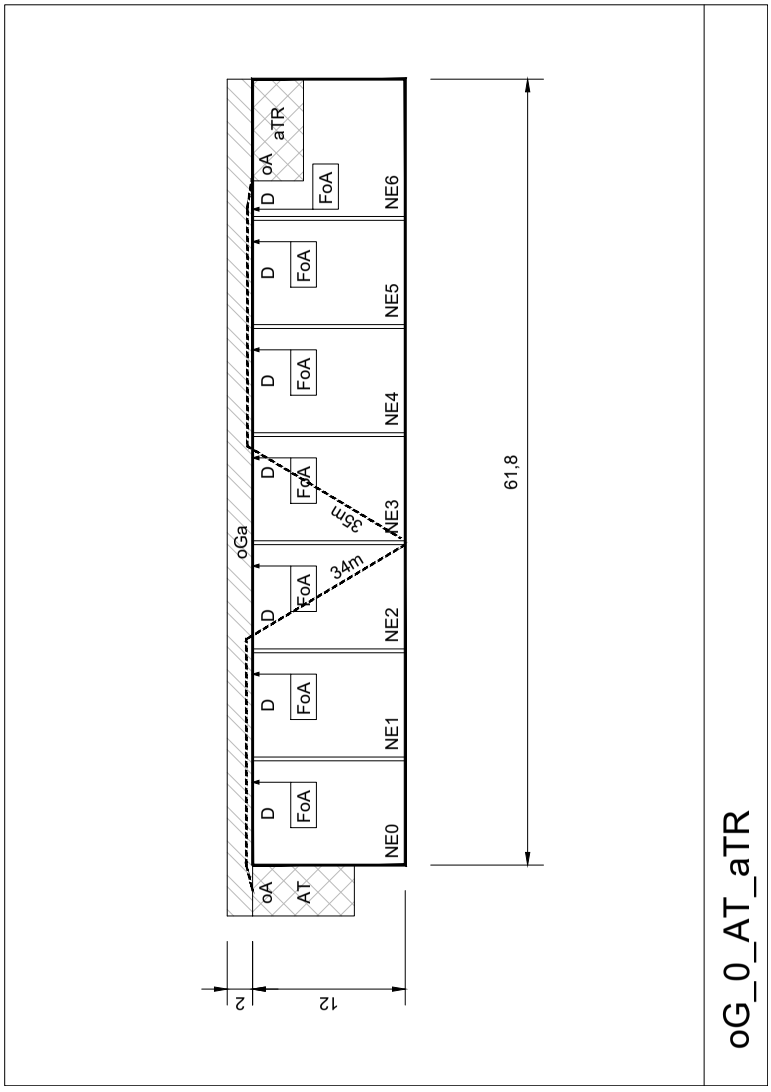


Fig. 19 Type floor plan for `oG_0_AT_aTR`.

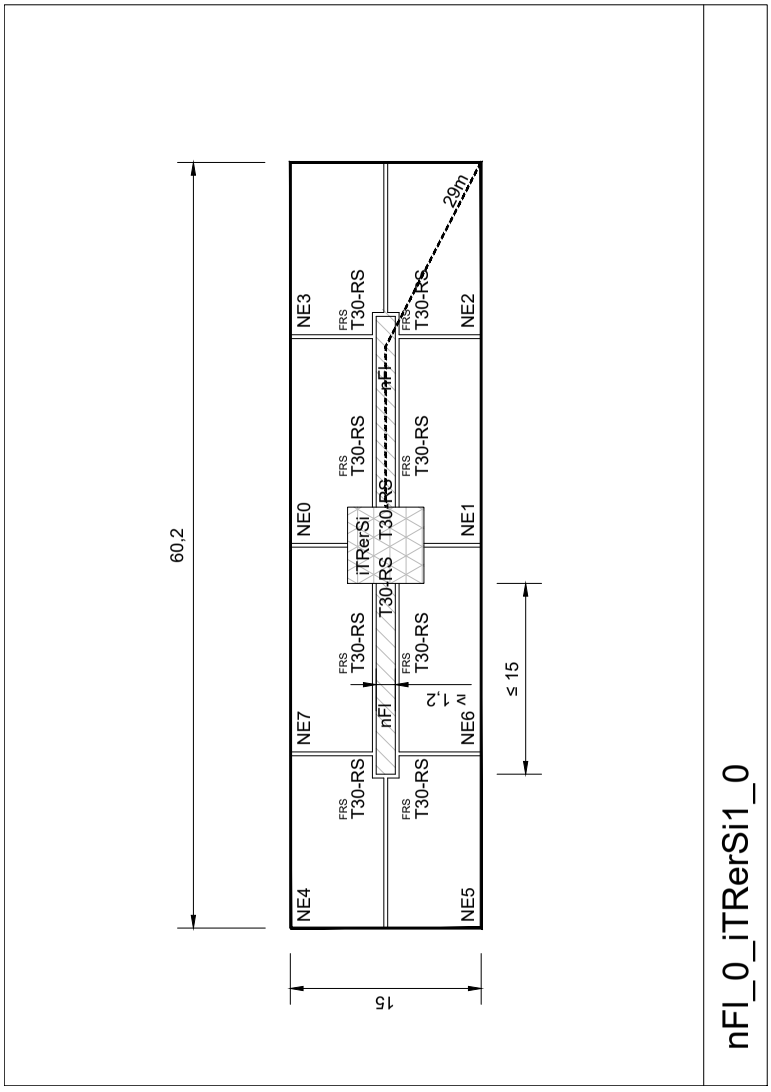


Fig. 20 Type floor plan for `nFl_0_iTRerSi1_0`.

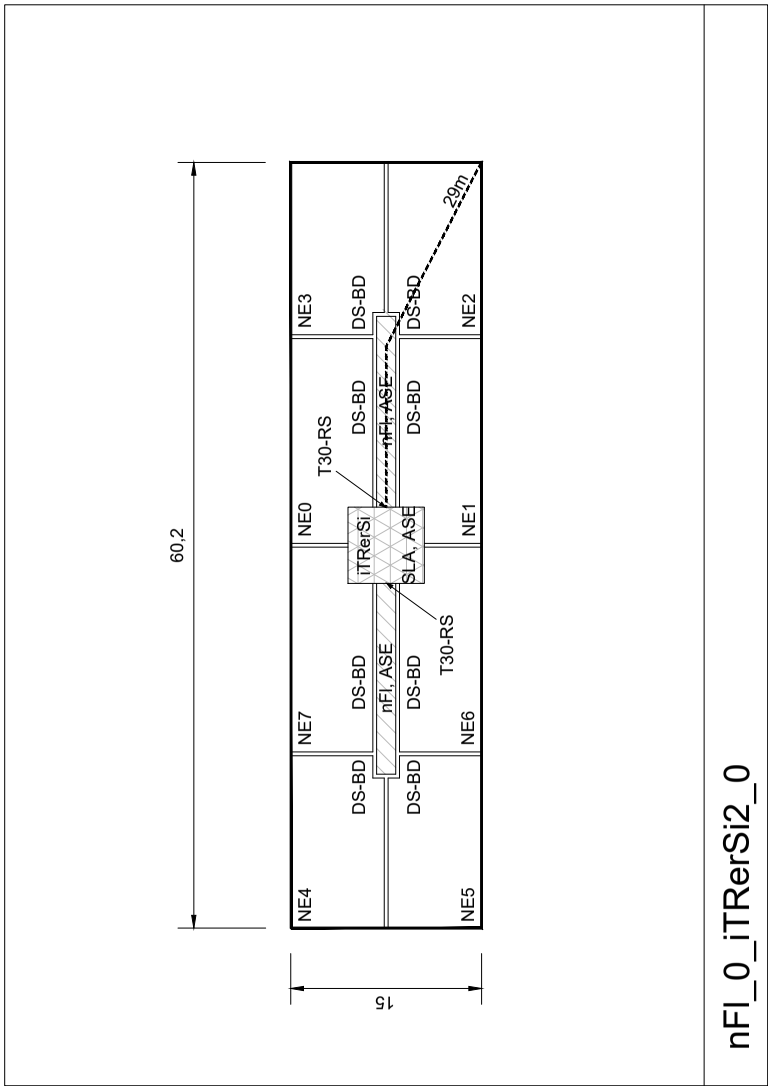


Fig. 21 Type floor plan for `nFl_0_iTRerSi2_0`.

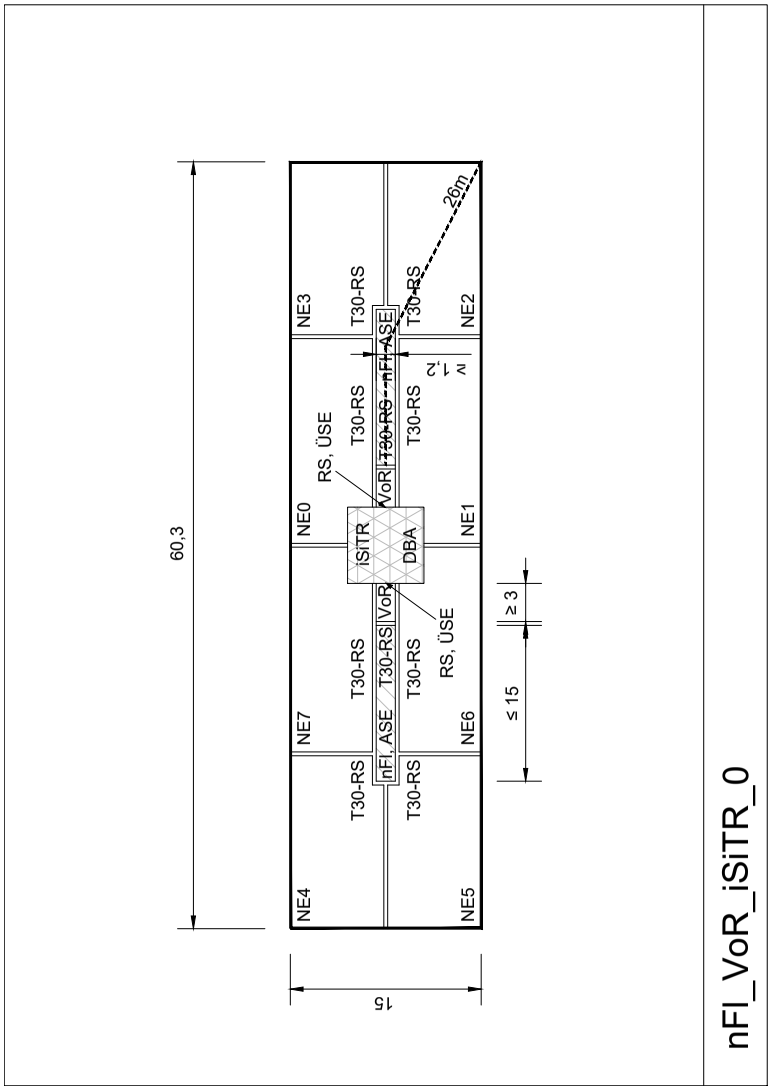


Fig. 22 Type floor plan for `nFl_VoR_iSiTR_0`.

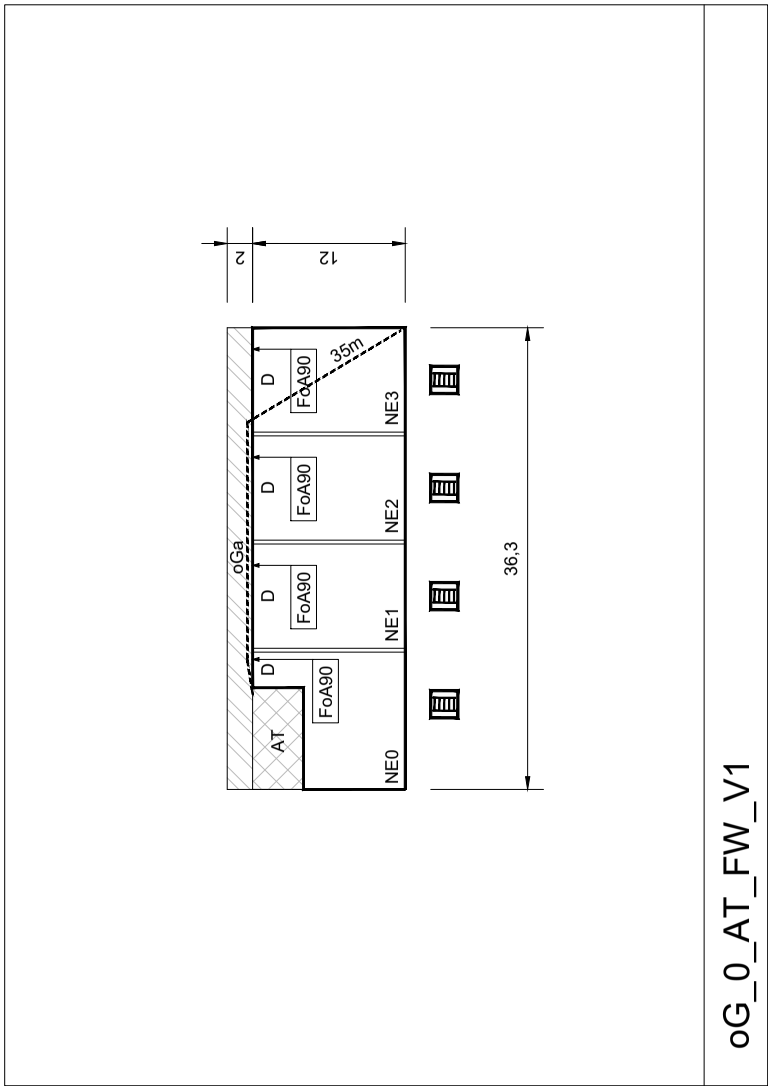


Fig. 23 Type floor plan for `oG_0_AT_FW_V1`.

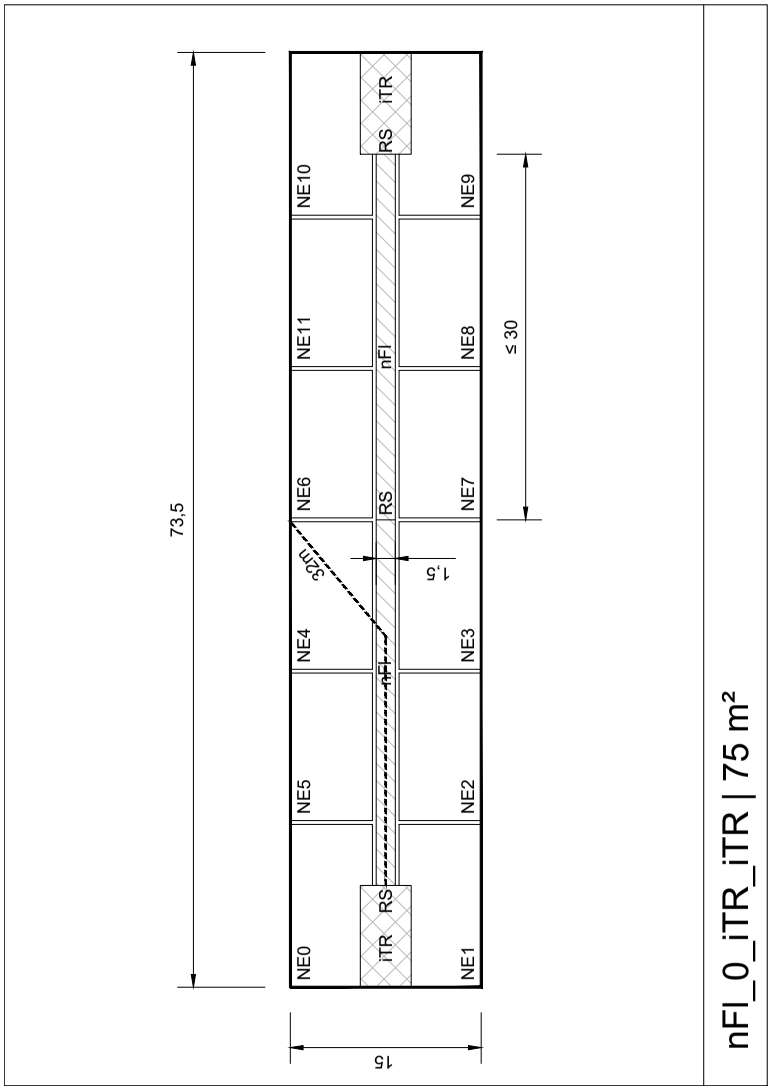


Fig. 24 Type floor plan for `nFl_0_iTR_iTR_75`.

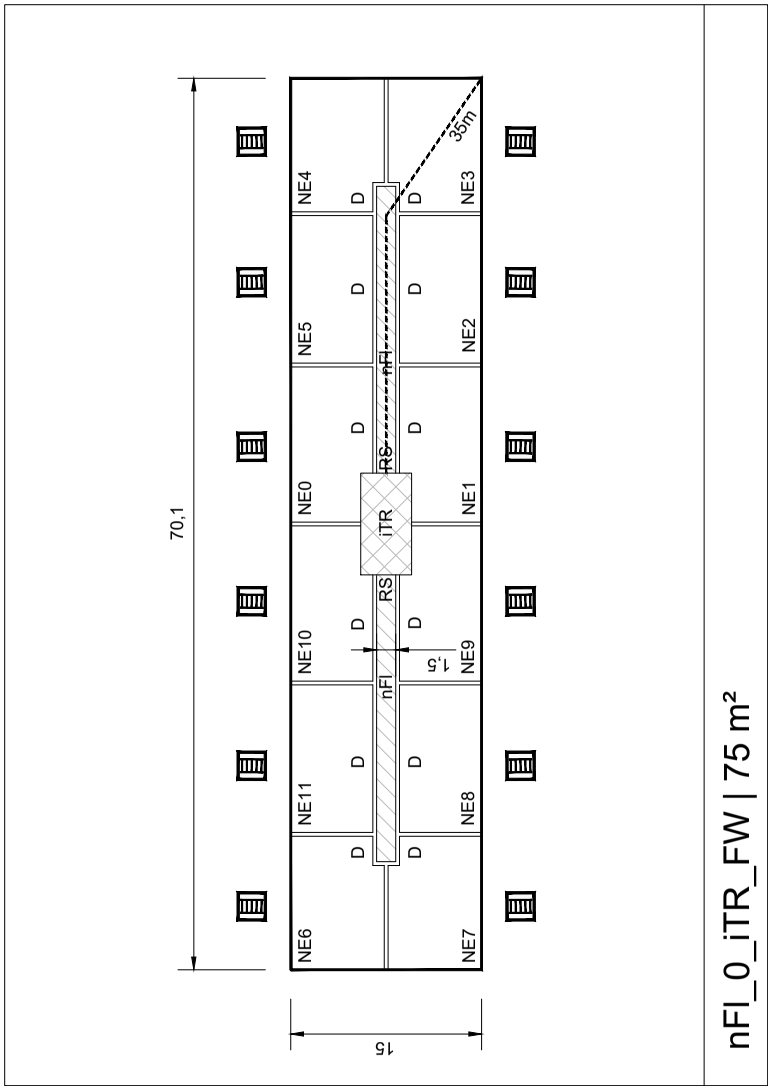


Fig. 25 Type floor plan for `nFl_0_iTR_FW_75`.

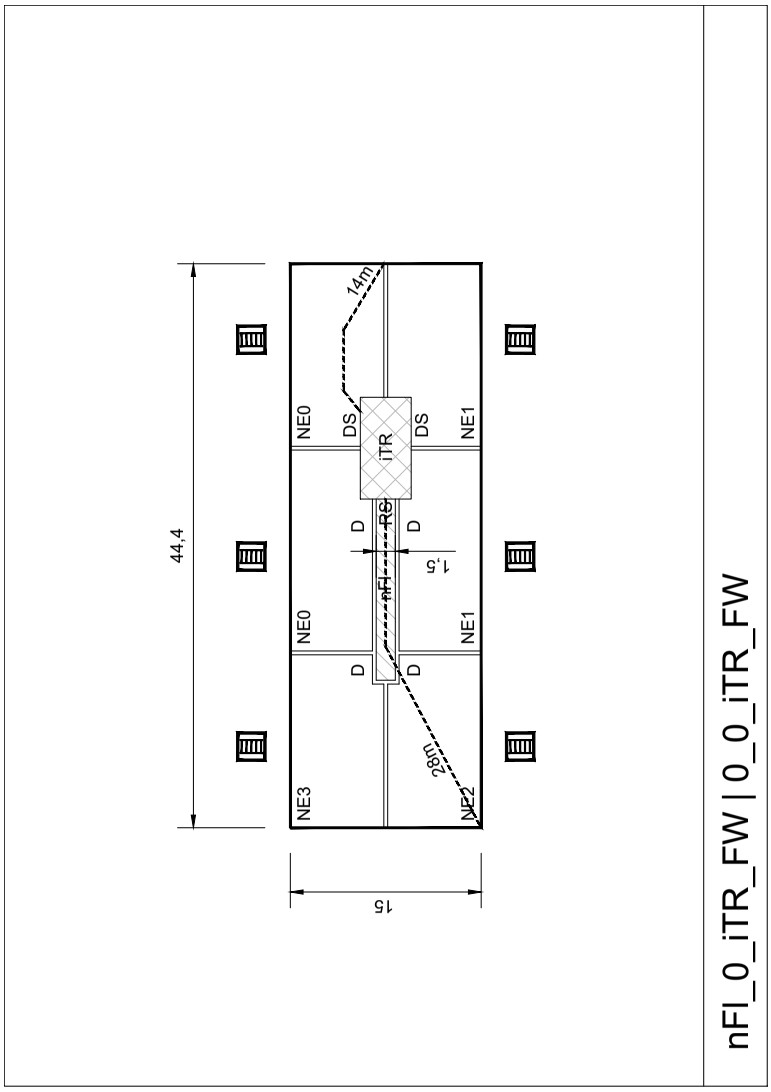


Fig. 26 Illustrative combination of the systems `nFl_0_iTR_FW` and `0_0_iTR_FW`. This drawing is not an additional model.

A.3 Basic-event input catalogue

Table 7 reproduces all 93 basic-event inputs used by the 21 models. "Input class" denotes one of the seven anchor levels (L1–L7) or a deliberately assigned special expert value. "Confidence" refers to the assessor's confidence in the assigned value, not to a statistical confidence interval. All current inputs are classified as confidence class 1, reflecting their origin in expert judgement. Additional confidence classes can be introduced in the future as empirical data become available. Time-dependent and influenceable are metadata for future model development and do not alter the present calculations. All entries have expert judgement as their numerical origin.

Table 7: Complete basic-event input catalogue.

Tag	Short description	Input	Class	Confidence	Time-dep.	Influenceable	Origin
PBraStift	Malicious arson	0.05	L1	1	no	no	Expert judgement
PBraABewohn	Fire ignition neg. occu.	0.15	special	1	no	no	Expert judgement
PBraANE0	Fire ignition in NE0	0.8	L6	1	no	no	Expert judgement
PAngstNERW2	Occu. fear response	0.05	L1	1	no	no	Expert judgement
PAngstNERW1	Occu. fear response	0.2	L2	1	no	no	Expert judgement
PAngstNE0	Occu. fear response	0.5	L4	1	no	no	Expert judgement
PFehlverhNEx	Occu. misconduct NEx	0.2	L2	1	no	yes	Expert judgement
PFahrBewohn	No fire safety awareness	0.35	L3	1	no	yes	Expert judgement
PFehlverhNE0	Occu. misconduct NE0	0.35	L3	1	no	yes	Expert judgement
PTürzurRett	Door opened for rescue	0.2	L2	1	no	yes	Expert judgement
PTT30zerst	Door NE0 T30RS burn	0.05	L1	1	no	no	Expert judgement
PTDSzerst	Door NE0 DS burn	0.65	L5	1	no	no	Expert judgement
PTDSBDzerst	Door NE0 DS BD burn	0.65	L5	1	no	no	Expert judgement
PTDzerst	Door NE0 D burn	0.65	L5	1	no	no	Expert judgement
PToAzerst	Door NE0 oA burn	0.8	L6	1	no	no	Expert judgement
PFoANE0oGa	Window NE0 open oGA	0.95	L7	1	no	no	Expert judgement
PT30RSNE1nFl0	D nFl_0 T30RS NE1 br	0.05	L1	1	no	no	Expert judgement
PT30RSNE1nFlF	D nFl_F T30RS NE1 br	0.05	L1	1	no	no	Expert judgement
PTDNE1oGaFW	D oGa_FW D NE1 br	0.2	L2	1	no	no	Expert judgement
PTDNE1oGa0	D oGa_0 D NE1 br	0.2	L2	1	no	no	Expert judgement
PToANE1oGa2R	D oGa 2R oA NE1 br	0.2	L2	1	no	no	Expert judgement
PTDSNE1iTR	D iTR DS NE1 br	0.35	L3	1	no	no	Expert judgement
PTDSNE1nFl	D nFl DS NE1 br	0.35	L3	1	no	no	Expert judgement
PTDNE1nFlFW	D nFl_FW D NE1 br	0.5	L4	1	no	no	Expert judgement
PTDSBDNE1	D nFl_0 DSBS NE1 br	0.5	L4	1	no	no	Expert judgement
PTDNE1nFl2R	D nFl 2R D NE1 br	0.5	L4	1	no	no	Expert judgement
PFoANE1oGaFW	W oGa_FW oA NE1 open	0.2	L2	1	no	no	Expert judgement
PFoANE1oG0	W oGa_0 oA NE1 open	0.2	L2	1	no	no	Expert judgement
PFoANE1oGa2R	W oGa 2R oA NE1 open	0.2	L2	1	no	no	Expert judgement
PTDNE2oGaFW	D oGa_FW D NE2 br	0.05	L1	1	no	no	Expert judgement
PTDNE2oGa0	D oGa_0 D NE2 br	0.05	L1	1	no	no	Expert judgement
PT30RSNE2nFl0	D nFl_0 T30RS NE2 br	0.05	L1	1	no	no	Expert judgement
PT30RSNE2nFlF	D nFl_F T30RS NE2 br	0.05	L1	1	no	no	Expert judgement
PToANE2oGa2R	D oGa 2R oA NE2 br	0.05	L1	1	no	no	Expert judgement
PTDSNE2iTR	D iTR DS NE2 br	0.2	L2	1	no	no	Expert judgement
PTDSNE2nFl	D nFl DS NE2 br	0.2	L2	1	no	no	Expert judgement
PTDNE2nFlFW	D nFl_FW D NE2 br	0.35	L3	1	no	no	Expert judgement
PTDSBDNE2	D nFl_0 DSBS NE2 br	0.35	L3	1	no	no	Expert judgement
PTDNE2nFl2R	D nFl 2R D NE2 br	0.35	L3	1	no	no	Expert judgement
PFoANE2oGaFW	W oGa_FW oA NE2 open	0.05	L1	1	no	no	Expert judgement
PFoANE2oGa0	W oGa_0 oA NE2 open	0.05	L1	1	no	no	Expert judgement
PFoANE2oGa2R	W oGa 2R oA NE2 open	0.05	L1	1	no	no	Expert judgement

Tag	Short description	Input	Class	Confidence	Time-dep.	Influenceable	Origin
PT30RSzerstnFl	D nFl T30RS iTRerSix br	0.05	L1	1	no	no	Expert judgement
PT30RSzerstVoR	D nFl T30RS VoR iSiTR br	0.05	L1	1	no	no	Expert judgement
PToAzerstoGa	D oGa oA aTR br	0.2	L2	1	no	no	Expert judgement
PToAoffennFL	D nFl oA AT open	0.2	L2	1	no	no	Expert judgement
PToAoffenoGa	D oGa oA aTR open	0.35	L3	1	no	no	Expert judgement
PTRSzerstoGafL	D nFl RS oGafL br	0.5	L4	1	no	no	Expert judgement
PTRSzerstnFl	D nFl RS iTR br	0.5	L4	1	no	no	Expert judgement
PToAzerstnFl	D nFl oA AT br	0.65	L5	1	no	no	Expert judgement
PDefektFTS	FSC NE0 priv. defec	0.2	L2	1	yes	yes	Expert judgement
PDefektOTS	ODC NE0 priv. defec	0.05	L1	1	yes	yes	Expert judgement
PmaniOTS	ODC NE0 priv. manipul	0.35	L3	1	yes	yes	Expert judgement
PmaniFTS	FSC NE0 priv. manipul	0.15	special	1	yes	yes	Expert judgement
PmaniOTSerhSi	ODC erh.Si NE0 manipul	0.2	L2	1	yes	yes	Expert judgement
PDefektOTSRW	ODC ER publ. defec	0.2	L2	1	yes	yes	Expert judgement
PmaniOTSRW	ODC ER publ. Manipul	0.2	L2	1	yes	yes	Expert judgement
PmaniOTSRS	ODC SMS manipul	0.2	L2	1	yes	yes	Expert judgement
PInstVorhoGa	Inst. in horiz. ER oGa	0.05	L1	1	yes	yes	Expert judgement
PInstVorhnFl	Inst. in horiz. ER nFl	0.2	L2	1	yes	yes	Expert judgement
PInstVorhiTR	Inst. in vert. ER iTR	0.2	L2	1	yes	yes	Expert judgement
PtechnDefekt	Failure occurs	0.05	L1	1	yes	yes	Expert judgement
PDefektRed	Redund. Component fail	0.025	special	1	yes	yes	Expert judgement
PStromfehlSSV	Power supply unav. EPS	0.025	special	1	yes	yes	Expert judgement
PDefekt	Component fail	0.05	L1	1	yes	yes	Expert judgement
PAnstfehl	Component not activated	0.05	L1	1	yes	yes	Expert judgement
PStromfehl	Power supply unavailable	0.05	L1	1	yes	yes	Expert judgement
PRauchoGfL0P	Smokecon. oGfL_0 ¿ TH	0.05	L1	1	no	no	Expert judgement
PRauchVoR0P	Smokecon. VoR_0 ¿ TH	0.05	L1	1	no	no	Expert judgement
PRauchATP	Smokecon. AT ¿ TH	0.2	L2	1	no	no	Expert judgement
PRauchoGa2RP	Smokecon. oG 2R ¿ TH	0.2	L2	1	no	no	Expert judgement
PRauchoGa0P	Smokecon. oG_0 ¿ TH	0.35	L3	1	no	no	Expert judgement
PRauchoGaFWP	Smokecon. oG_FW ¿ TH	0.35	L3	1	no	no	Expert judgement
PRauchiTRP	Smokecon. iTR ¿ TH	0.5	L4	1	no	no	Expert judgement
PRauchaTRP	Smokecon. aTR ¿ TH	0.5	L4	1	no	no	Expert judgement
PRauchnFl2RP	Smokecon. nFl 2R ¿ TH	0.5	L4	1	no	no	Expert judgement
PRauchnFl0P	Smokecon. nFl_0 ¿ TH	0.8	L6	1	no	no	Expert judgement
PRauchnFlFWP	Smokecon. nFl_FW ¿ TH	0.8	L6	1	no	no	Expert judgement
PTempATP	Temp. AT ¿ TH	0.05	L1	1	no	no	Expert judgement
PTempoGfL0P	Temp. oGfL_0 ¿ TH	0.05	L1	1	no	no	Expert judgement
PTempoGa2RP	Temp. oG 2R ¿ TH	0.05	L1	1	no	no	Expert judgement
PTempoGa0P	Temp. oG_0 ¿ TH	0.2	L2	1	no	no	Expert judgement
PTempoGaFWP	Temp. oG_FW ¿ TH	0.2	L2	1	no	no	Expert judgement
PTempiTRP	Temp. iTR ¿ TH	0.35	L3	1	no	no	Expert judgement
PTempaTRP	Temp. aTR ¿ TH	0.35	L3	1	no	no	Expert judgement
PTempnFl2RP	Temp. nFl 2R ¿ TH	0.35	L3	1	no	no	Expert judgement

Tag	Short description	Input	Class	Confidence	Time-dep.	Influenceable	Origin
PTempVoR0P	Temp. VoR_0 ¿ TH	0.5	L4	1	no	no	Expert judgement
PTempnFl0P	Temp. nFl_0 ¿ TH	0.65	L5	1	no	no	Expert judgement
PTempnFlFWP	Temp. nFl_FW ¿ TH	0.65	L5	1	no	no	Expert judgement
PoGfLbeeinoG	oGa compr. oGafL	0.05	L1	1	no	no	Expert judgement
PATbeeinoGa	oGa compr. AT	0.2	L2	1	no	no	Expert judgement
PkeineFB	No fire safety inspection	0.8	L6	1	yes	yes	Expert judgement
PvRWPers	Incapacita. occu. verti. ER	0.0001	special	1	no	no	Expert judgement

A.4 Complete fault trees

The following diagrams are the complete fault-tree outputs for the 21 configurations used in the article. Their order follows the systematic model order of Appendix A.2, not the ranking of the results.

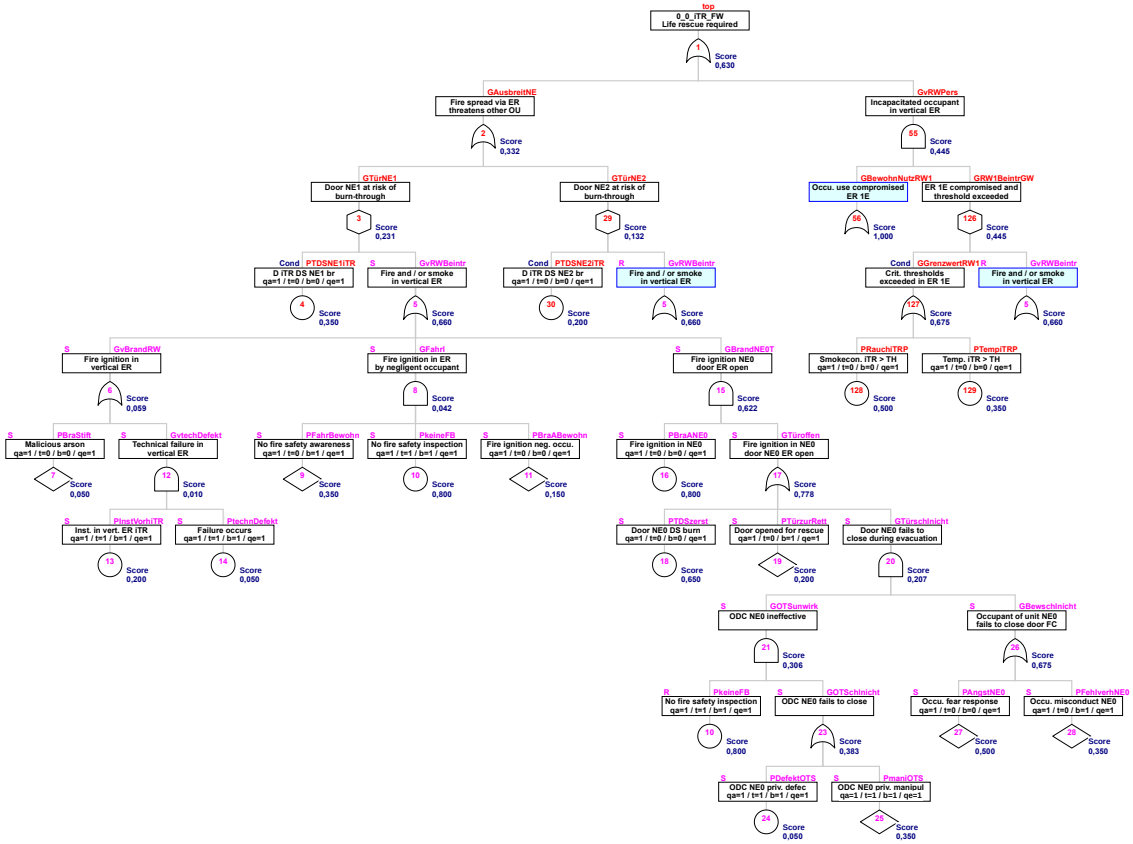


Fig. 27 Complete fault tree for `0_0_iTR_FW`.

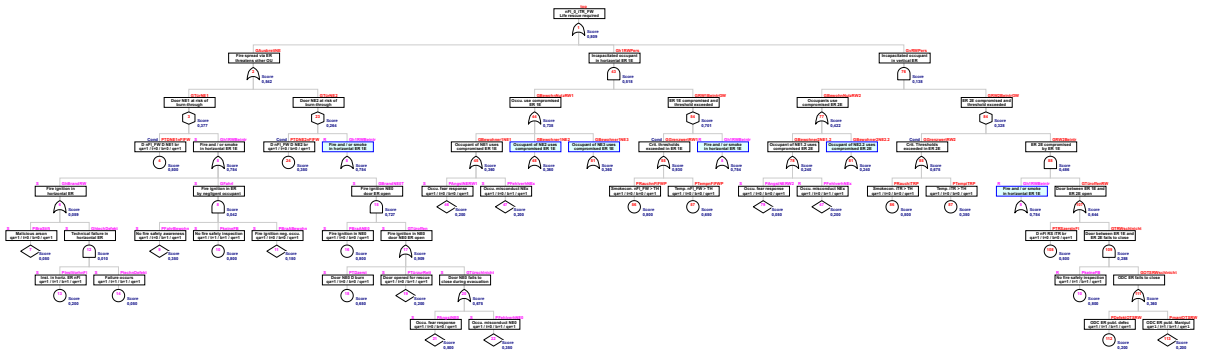


Fig. 28 Complete fault tree for `nFl_O_iTR_FW`.

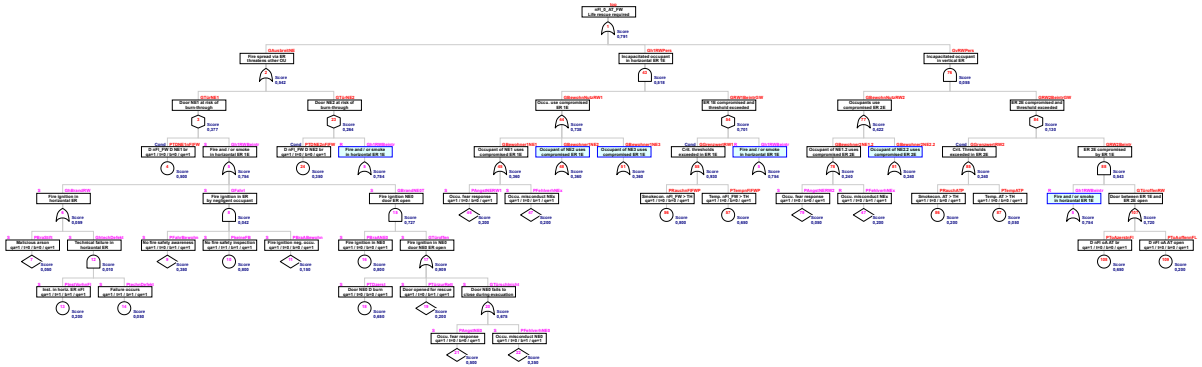


Fig. 29 Complete fault tree for `nFl_O_AT_FW`.

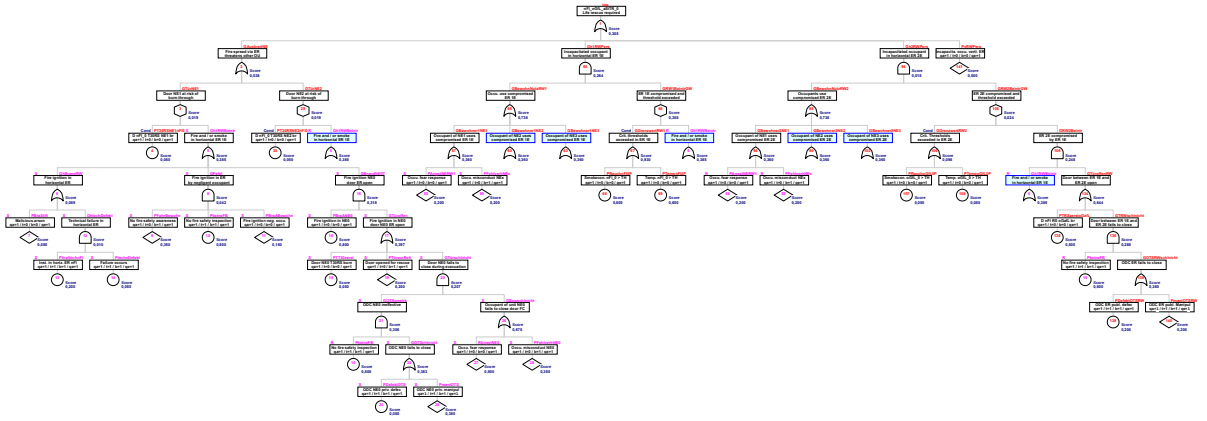


Fig. 30 Complete fault tree for `nFl_oGfL_aSiTR_0`.

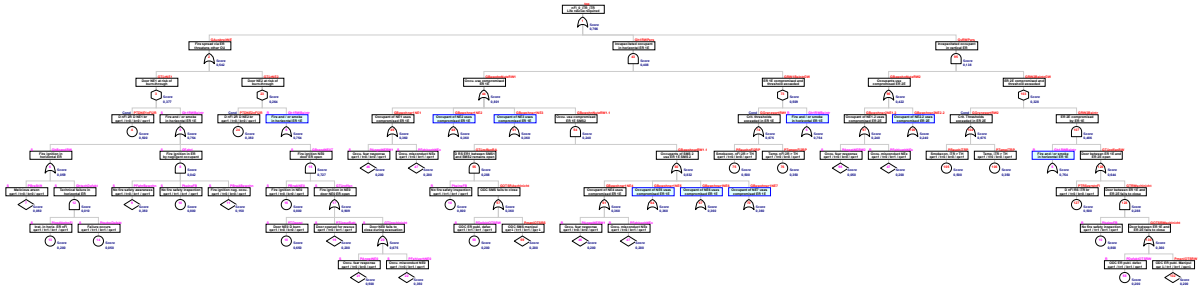


Fig. 31 Complete fault tree for `nFl_0_iTR_iTR`.

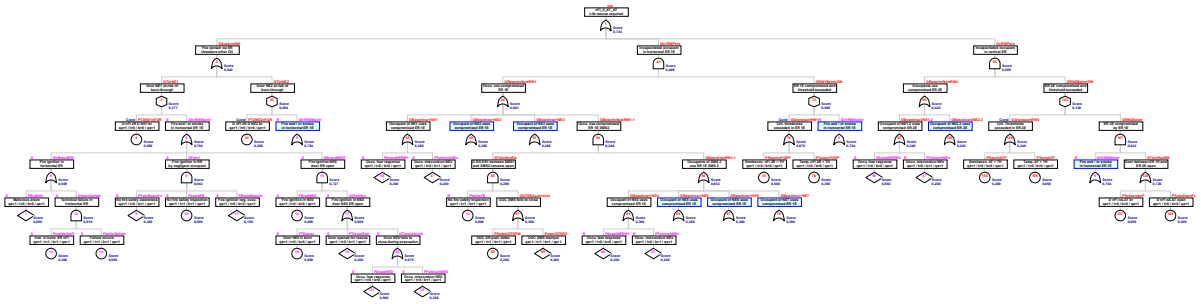


Fig. 32 Complete fault tree for `nFl_0_AT_AT`.

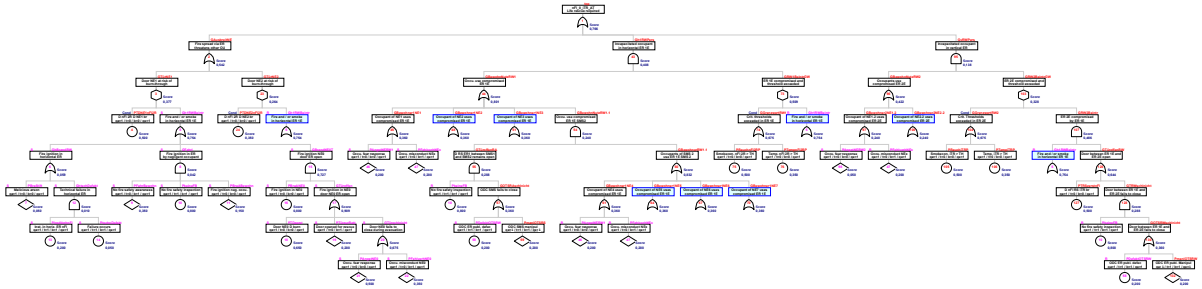


Fig. 33 Complete fault tree for `nFl_O_iTR_AT`.

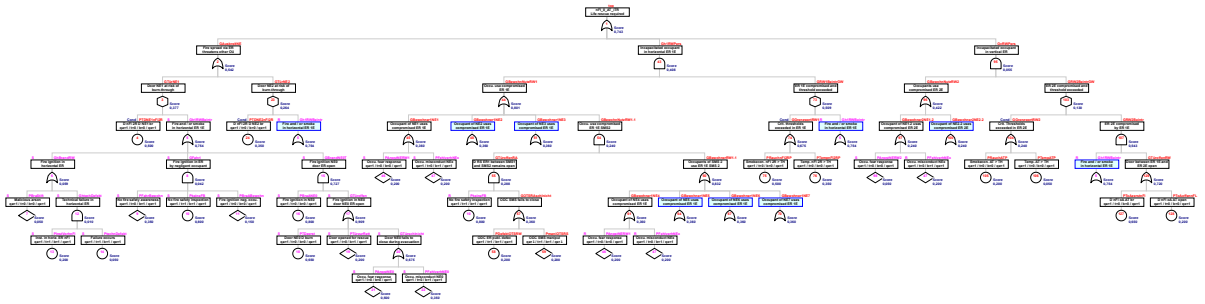


Fig. 34 Complete fault tree for `nFl_0_AT_iTR`.

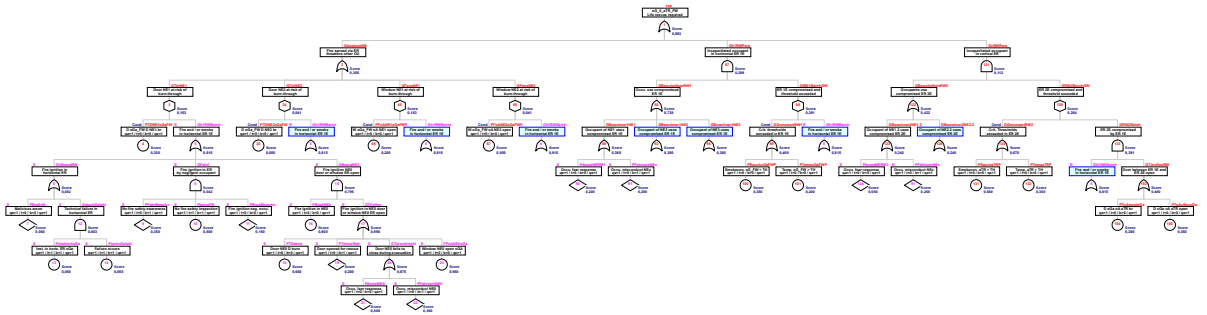


Fig. 35 Complete fault tree for `oG_0_aTR_FW`.

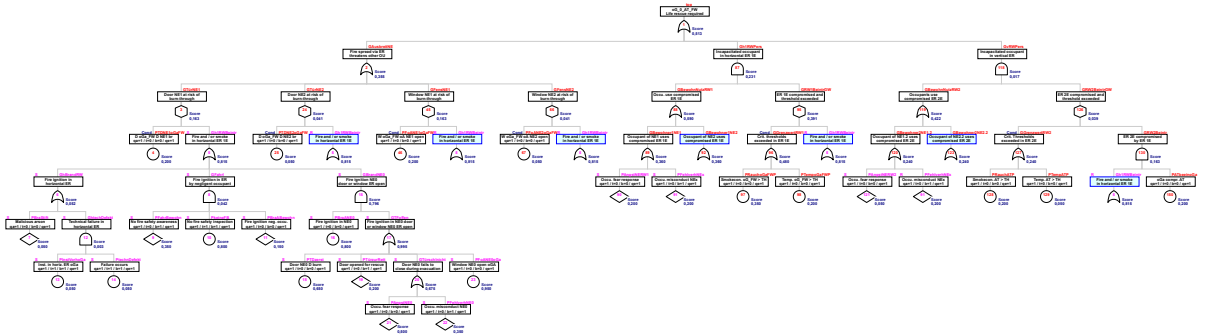


Fig. 36 Complete fault tree for `oG_0_AT_FW`.

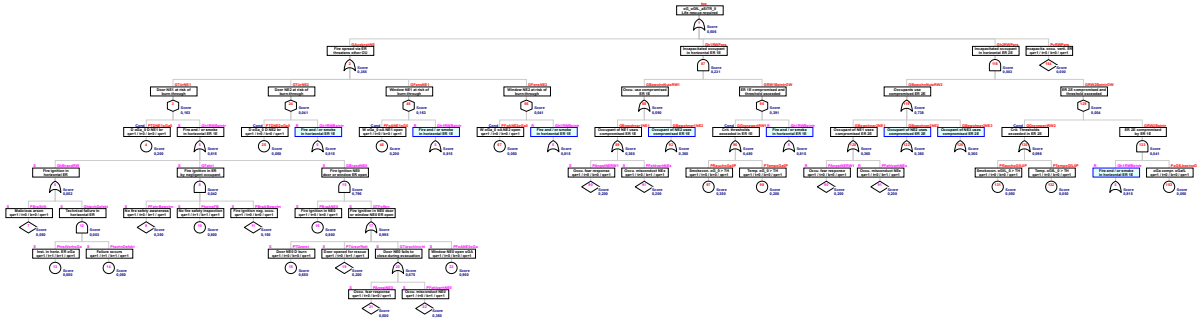


Fig. 37 Complete fault tree for `oG_oGfL_aSiTR_0`.

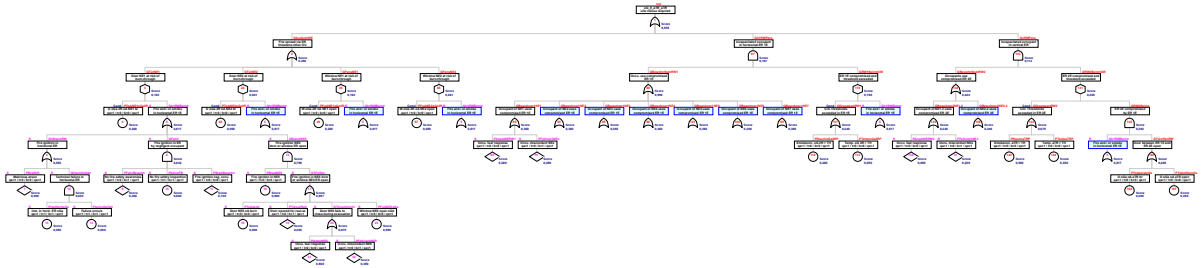


Fig. 38 Complete fault tree for `oG_0_aTR_aTR`.

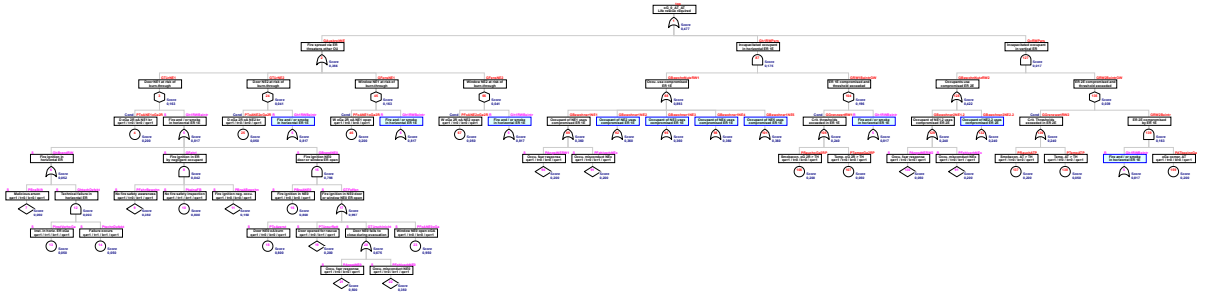


Fig. 39 Complete fault tree for `oG_0_AT_AT`.

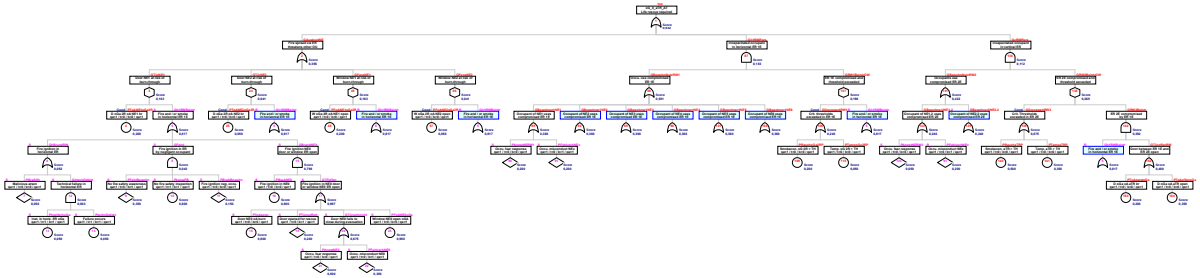


Fig. 40 Complete fault tree for `oG_0_aTR_AT`.

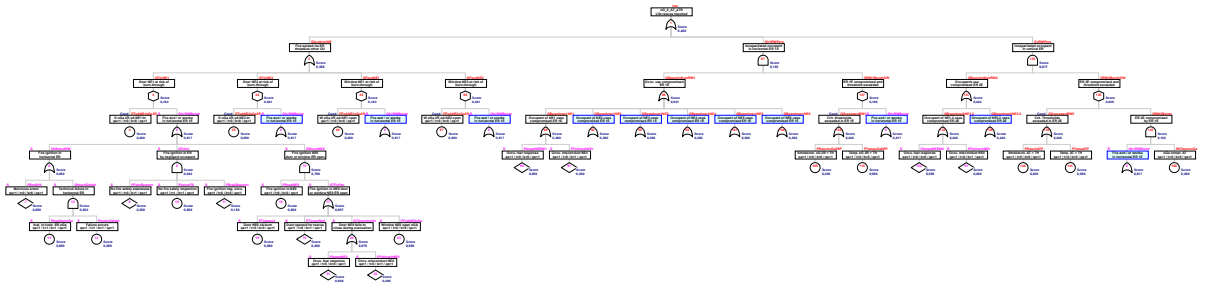


Fig. 41 Complete fault tree for `oG_0_AT_aTR`.

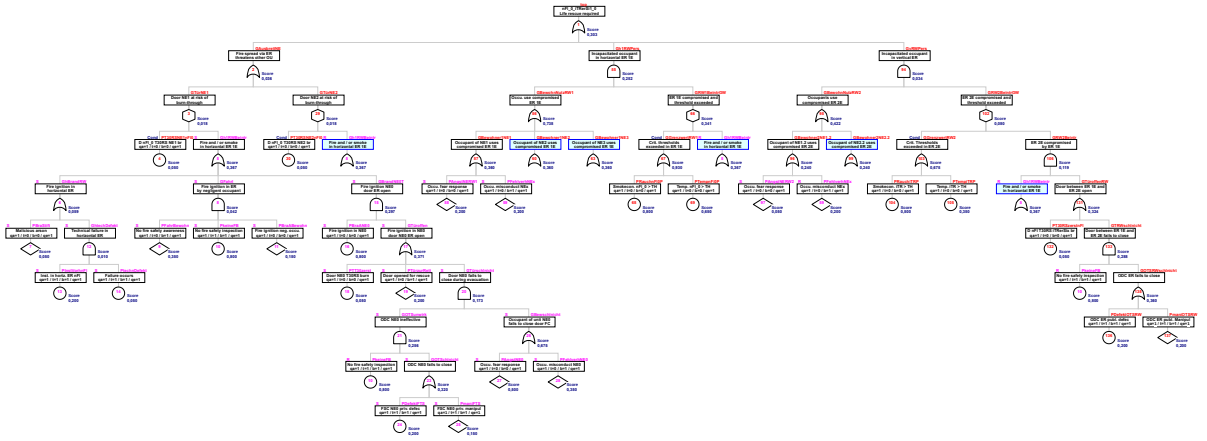


Fig. 42 Complete fault tree for `nFl_0_iTRerSi1_0`.

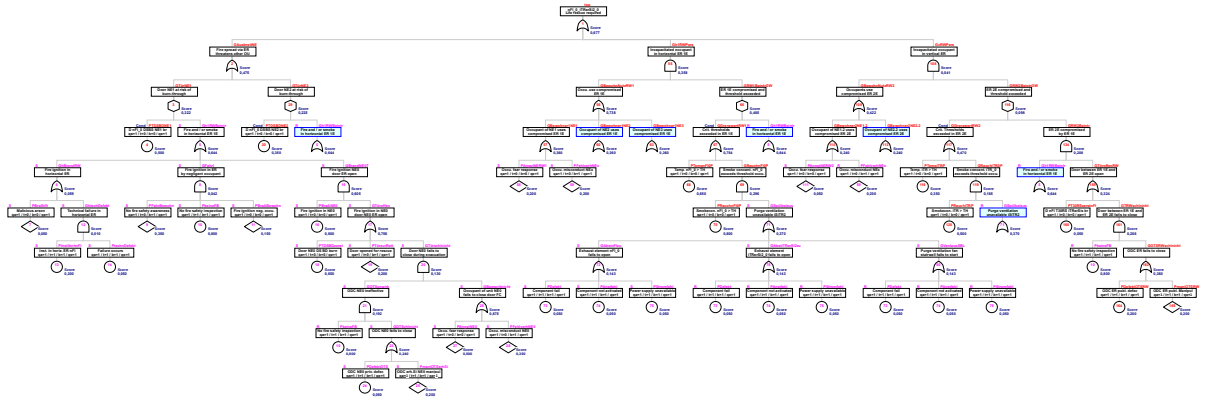


Fig. 43 Complete fault tree for `nFl_0_iTRerSi2_0`.

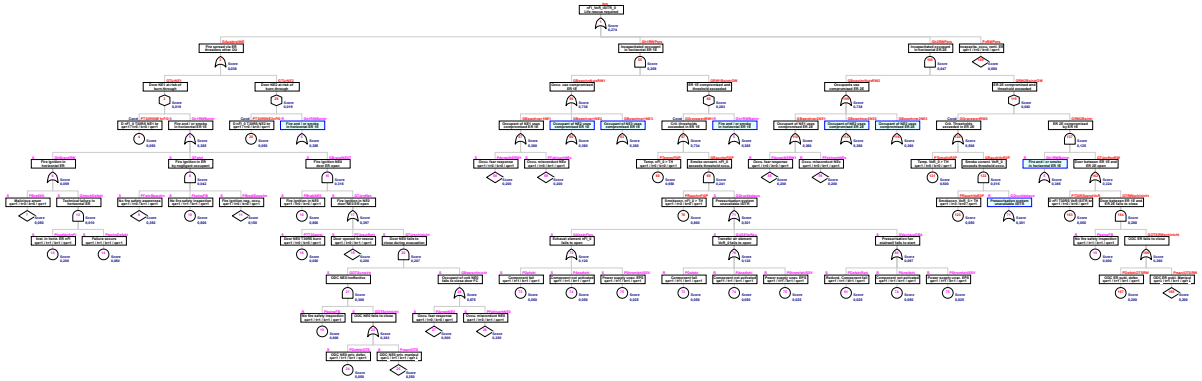


Fig. 44 Complete fault tree for `nFl_VoR_iSiTR_0`.

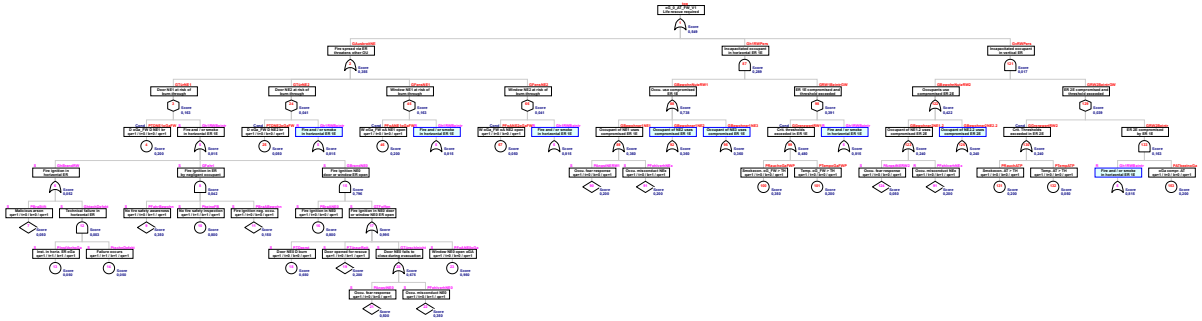


Fig. 45 Complete fault tree for `oG_0_AT_FW_V1`.

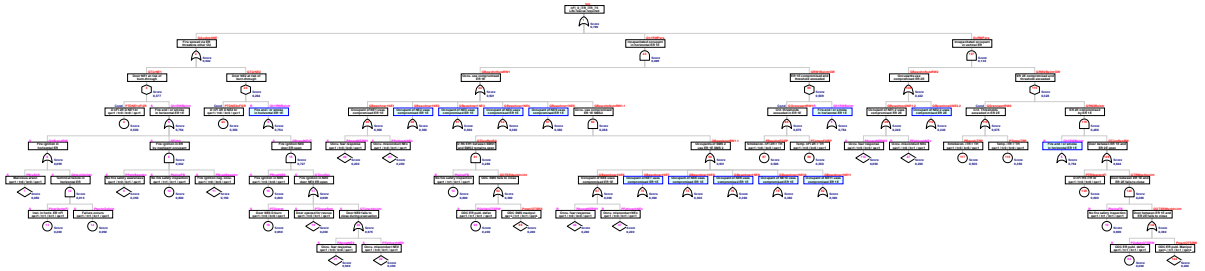


Fig. 46 Complete fault tree for `nFl_0_iTR_iTR_75`.

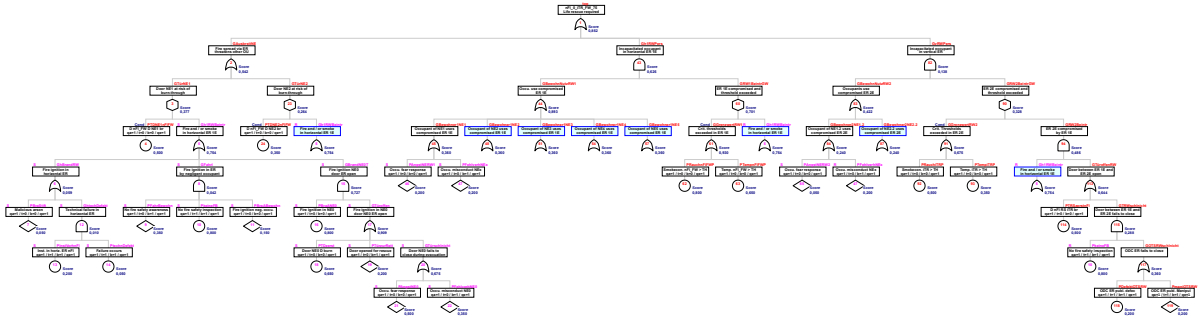


Fig. 47 Complete fault tree for `nFl_0_iTR_FW_75`.