



A probabilistic system dynamics model for dynamic assessment of occupant risk during fire growth and evacuation

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ABSTRACT

Fires in buildings pose a significant threat to occupant life safety, particularly when fire growth, smoke-layer descent, evacuation delay, and exit-capacity limitations evolve on comparable time scales. This study develops a probabilistic System Dynamics framework for screening-level assessment of occupant exposure during fire growth and evacuation. The model integrates a smoke-layer-based Available Safe Egress Time calculation with an aggregated evacuation model including detection, recognition and response, travel time, queue formation, and total effective exit capacity. Occupants are represented through three stocks: occupants remaining inside the evacuation zone, occupants safely evacuated before untenability, and occupants exposed to untenable conditions. Uncertainty in fire growth, critical smoke-free height, smoke-layer modelling, response time, movement velocity, specific flow capacity, and evacuation timing is propagated through stochastic simulation. The framework is applied to a near-critical retail evacuation-zone scenario in which ASET and RSET are of similar magnitude. Scenario analysis shows that alarm delay, enclosure height, and fire-growth severity are dominant drivers of exposure. Increasing additional alarm delay from 0 to 720 s increases the probability of evacuation failure from 0.0117 to 0.9282, while increasing enclosure height from 2.2 to 3.6 m reduces the expected number of exposed occupants from 160.68 to 14.30. The results demonstrate that the proposed framework can identify near-critical conditions, quantify probabilistic ASET/RSET competition, and support early-stage comparison of fire safety design and operational strategies. The model is intended as a screening and decision-support tool, complementary to detailed fire and evacuation simulations.

1. introduction

Fire safety in buildings remains a central concern for architects, engineers, safety professionals, and emergency planners, particularly as modern buildings become larger, more complex, and more highly occupied. Fires in enclosed environments can produce severe human, economic, and societal consequences, making Fire Safety Engineering (FSE) an essential component of loss prevention and risk management. Occupant safety during a fire depends on the interaction between fire development, tenability conditions, warning, human response,

movement, and exit capacity. The dynamic and uncertain nature of these processes makes evacuation safety a challenging problem for both design and emergency management (Ronchi, 2021; Johansson and Svensson, 2019).

The assessment of safe evacuation is commonly framed through the relationship between the Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET). ASET represents the time available before untenable conditions occur, while RSET represents the time required for occupants to detect the event, recognize the need to evacuate, respond, travel to exits, and pass through the exit system (Fahy,

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2016; Hurley and Rosenbaum, 2016). Safe evacuation is generally achieved when RSET is lower than ASET. However, both quantities are uncertain. ASET depends on fire-growth rate, smoke-layer development, enclosure geometry, and tenability criteria, whereas RSET depends on detection, alarm delay, recognition and response, movement speed, exit capacity, and queuing (Kuligowski, 2016a, 2016b).

Human behaviour in fire further increases this uncertainty. Occupants may not respond immediately to alarm signals, may seek additional information, may follow familiar routes, or may be affected by smoke, visibility, stress, and social influence (Akizuki, 2016; Fahy, 2016). As emphasized in fire safety engineering literature, evacuation performance cannot be fully characterized using a single deterministic value, because both fire development and occupant response vary from one scenario to another (Hurley et al., 2016). This is particularly important in near-critical conditions, where moderate changes in detection delay, fire growth, exit capacity, or response time can determine whether occupants evacuate before or after the onset of untenability.

Traditional fire safety analyses often evaluate fire development and evacuation as separate or sequential processes. Deterministic ASET/RSET comparisons provide a useful basis for performance-based assessment, but they may not fully represent accumulations, time delays, feedback relationships, and uncertainty in the evolution of fire-evacuation scenarios. High-resolution methods, such as computational fluid dynamics and agent-based evacuation models, can provide detailed spatial and behavioural information, but they often require substantial input data and computational effort. Complementary screening-level methods are therefore useful for representing the system-level interaction between fire-induced tenability loss and evacuation performance while enabling rapid scenario testing under uncertainty.

System Dynamics (SD) provides a suitable modelling approach for this purpose. SD represents systems through stocks, flows, auxiliary variables, feedback relationships, and delays, allowing the modeller to describe how accumulations and rates evolve over time (Martín García, 2006; Sterman, 2002). In safety and loss-prevention research, SD has been used to examine dynamic accident processes, emergency response, organizational behaviour, and evolving risk conditions (Wang et al., 2019; Xu et al., 2021; Dueñas Santana et al., 2024, 2025). In the context of evacuation and fire safety, SD has also been applied to investigate evacuation behaviour and emergency response in complex environments (Li et al., 2022; Kumar et al., 2022), while recent review work has highlighted the broader potential of systems thinking and SD in fire safety engineering (Dueñas Santana et al., 2026). These studies show the potential of SD for representing system-level behaviour where delays, feedbacks, and accumulations are important.

Despite these developments, further work is needed to formulate transparent and reproducible SD models that combine fire-induced tenability loss, evacuation flow, queue formation, and probabilistic uncertainty within a fire safety engineering framework. In particular, fewer studies explicitly evaluate the probabilistic competition between ASET and RSET using stock-flow representations of occupants remaining inside, occupants safely evacuated, and occupants exposed to untenable conditions. This distinction is important because direct fatality prediction requires explicit vulnerability or dose-response models, whereas exposure to untenable conditions can be evaluated more transparently from the ASET/RSET relationship.

This paper develops a probabilistic System Dynamics framework for screening-level assessment of occupant exposure during fire growth and evacuation. The model combines a smoke-layer-based ASET calculation with an aggregated evacuation model that includes detection, recognition and response, travel time, total effective exit width, exit capacity, and queuing. Occupants are represented through three main stocks: occupants remaining inside the evacuation zone, occupants safely evacuated before untenability, and occupants exposed to untenable conditions. The model preserves occupant mass balance and evaluates exposure as the number of occupants not safely evacuated when ASET is

reached.

Uncertainty is incorporated by assigning probability distributions to key fire and evacuation variables, including fire-growth rate, critical smoke-free layer height, smoke-model uncertainty, response time, movement velocity, specific flow capacity, and RSET uncertainty. Stochastic simulation is then used to estimate probabilistic output indicators, including the expected number of exposed occupants, the probability that full evacuation time exceeds ASET, threshold-based exposure probabilities, and the distribution of the evacuation safety margin.

The contribution of this study is threefold. First, it provides a transparent SD stock-flow formulation linking fire-induced tenability loss with evacuation progress through the ASET/RSET criterion. Second, it introduces an exposure-based endpoint that avoids unsupported fatality estimation while preserving a meaningful life-safety consequence indicator. Third, it demonstrates how probabilistic simulation and scenario analysis can identify dominant risk drivers, including alarm delay, enclosure height, fire-growth severity, total effective exit width, enclosure area, and detection mode.

The framework is demonstrated using a near-critical retail evacuation-zone scenario in which ASET and RSET are of similar magnitude. This allows the model to evaluate how uncertainty and parameter changes shift the system between successful evacuation and exposure to untenable conditions. The results are intended to support screening-level decision-making, identification of critical scenarios, and prioritization of cases requiring more detailed fire or evacuation modelling.

2. methodology

The methodology develops a probabilistic System Dynamics (SD) framework for screening-level assessment of occupant exposure during fire growth and evacuation. The framework combines a simplified fire-tenability module, an aggregated evacuation module, and uncertainty propagation through stochastic simulation. The objective is not to reproduce detailed spatial fire dynamics or individual pedestrian trajectories, but to evaluate how uncertainty in fire development, detection, response, movement, and exit capacity affects the dynamic balance between Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET).

The model estimates the time-dependent evolution of occupants remaining inside the evacuation zone, occupants safely evacuated before untenability, and occupants exposed to untenable conditions. Fire growth and smoke-layer descent determine ASET, while detection, recognition and response, travel, exit capacity, and queue formation determine evacuation progress and RSET-related indicators. The interaction between these processes is evaluated by comparing evacuation progress with the onset of untenable conditions.

2.1. Modelling scope and framework overview

The model is intended as a screening-level decision-support tool for comparing fire-evacuation scenarios and identifying dominant risk drivers. It is suitable for evaluating relative changes in evacuation performance caused by design and operational parameters such as alarm delay, total effective exit width, enclosure geometry, fire-growth severity, and detection mode. It is not intended to predict the exact outcome of a specific fire event.

The fire environment is represented as a single compartment or evacuation zone. Fire development is described using a simplified smoke-layer formulation, and untenable conditions are assumed to occur when the smoke layer descends to a critical smoke-free height. This allows ASET to be calculated consistently with the aggregated SD formulation. Detailed spatial variations in temperature, toxic species, visibility, and local smoke movement are outside the scope of the model.

Occupants are represented as an aggregated population rather than

as individual agents. The model does not explicitly simulate individual trajectories, route choice, group behaviour, social interaction, or adaptive decision-making. Instead, occupant response and movement are represented through probabilistic variables, including detection time, recognition and response time, movement speed, initial location, evacuation-flow capacity, and uncertainty factors.

The exit system is represented through the total effective exit width, W_{tot} , rather than by a single physical door. This parameter represents the combined useable width of the exits available to occupants in the modelled evacuation zone. The exit capacity is then calculated from W_{tot} and the specific flow capacity. This formulation allows multiple exits to be represented within an aggregated stock-flow structure.

The consequence endpoint is exposure to untenable conditions. Occupants are considered safely evacuated only if they leave the evacuation zone before ASET. Occupants still inside the zone when ASET is reached are conservatively classified as exposed to untenable conditions. This exposure-based endpoint is used instead of direct fatality prediction because the model does not include a vulnerability or dose-response relationship.

The framework distinguishes between endogenous evacuation/exposure feedbacks and exogenous fire-tenability forcing. Evacuation, queue formation, and exposure are represented through the SD stock-flow structure. Fire growth is treated as an uncertain exogenous driver of smoke-layer descent and ASET; therefore, the model does not assume

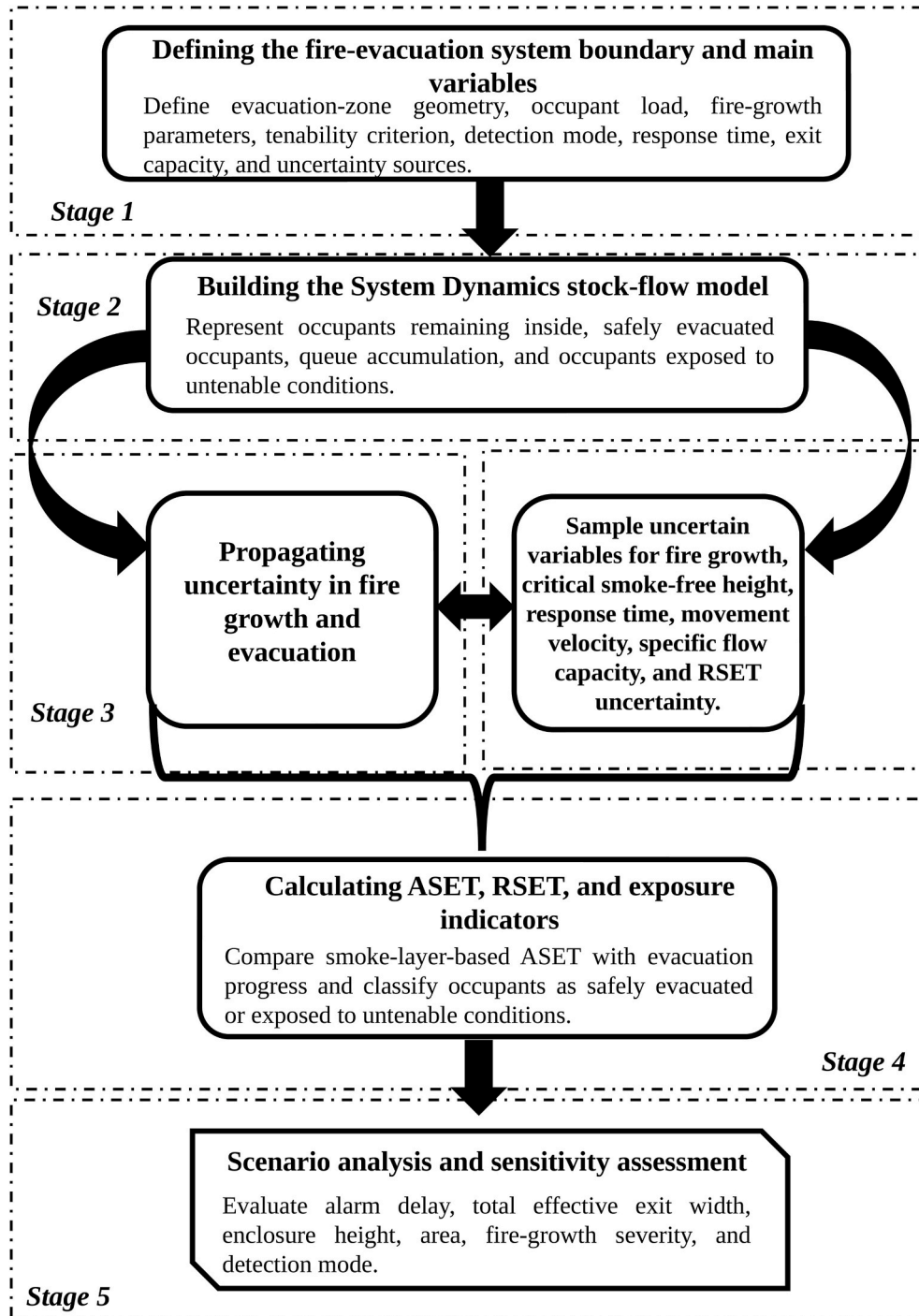


Fig. 1. Probabilistic System Dynamics methodology for assessing occupant exposure during fire growth and evacuation.

that occupant movement physically modifies fire development. The coupling represented in the model is from fire development to tenability loss, and from evacuation performance to occupant exposure.

The modelling sequence is summarized in Fig. 1. Uncertain input variables are sampled and propagated through the fire-tenability and evacuation modules. The smoke-layer calculation provides ASET, while the evacuation module provides the time evolution of occupants remaining inside, safely evacuated occupants, queue accumulation, and exposed occupants. Repeating this process over many stochastic realizations allows the model to estimate probabilistic indicators such as the expected number of exposed occupants, the probability that RSET exceeds ASET, and the distribution of the evacuation safety margin.

2.2. Stock-flow structure and feedback relationships

The SD model represents evacuation life safety through three main occupant stocks: occupants remaining inside the evacuation zone, $N_{in}(t)$, occupants safely evacuated before untenability, $N_{safe}(t)$, and occupants exposed to untenable conditions, $N_{exp}(t)$. The initial occupant population is calculated from the evacuation-zone area and occupant load density:

$$N_0 = A_E \rho \quad (1)$$

where A_E is the evacuation-zone area and ρ is the occupant load density. At any time, occupant conservation is expressed as:

$$N_0 = N_{in}(t) + N_{safe}(t) + N_{exp}(t) \quad (2)$$

Before untenable conditions occur, occupants leave the evacuation zone through the evacuation flow, $Q_{evac}(t)$. The stock-flow equations are:

$$\frac{dN_{safe}(t)}{dt} = Q_{evac}(t) \quad (3)$$

$$\frac{dN_{in}(t)}{dt} = -Q_{evac}(t) \quad (4)$$

$$\frac{dN_{exp}(t)}{dt} = 0 \quad (5)$$

Untenability is assumed to occur at ASET, defined as the first time at which the smoke layer reaches the critical smoke-free height. At this point, occupants who have not safely evacuated are classified as exposed:

$$N_{exp}(ASET) = N_0 - N_{safe}(ASET) \quad (6)$$

After ASET, the occupant state is considered final for the screening-level exposure assessment:

$$N_{in}(t \geq ASET) = 0 \quad (7)$$

$$N_{safe}(t \geq ASET) = N_{safe}(ASET) \quad (8)$$

$$N_{exp}(t \geq ASET) = N_0 - N_{safe}(ASET) \quad (9)$$

Queue formation is represented as an intermediate accumulation between occupant arrival at the exit system and discharge through the exits. Let $N_{queue}(t)$ be the number of occupants waiting at the exits. The queue evolves as:

$$\frac{dN_{queue}(t)}{dt} = Q_{arr}(t) - Q_{evac}(t) \quad (10)$$

where $Q_{arr}(t)$ is the arrival rate at the exit system. The evacuation flow is limited by the number of queued occupants and by the exit capacity:

$$Q_{evac}(t) = \min \left[\frac{N_{queue}(t)}{\Delta t}, C_{exit} \right] \quad (11)$$

where Δt is the numerical time step and C_{exit} is the total exit capacity.

The exit capacity is calculated from the total effective exit width:

$$C_{exit} = F_s W_{tot} \quad (12)$$

$$W_{tot} = \sum_{i=1}^{n_e} W_i \quad (13)$$

where F_s is the specific flow capacity, W_i is the useable width of exit i , and n_e is the number of representative exits.

The feedback structure arises from the interaction among occupant accumulation, evacuation flow, queue formation, and exposure. Evacuation acts as a balancing feedback because it reduces the number of occupants remaining inside. Exit capacity introduces a capacity-limiting feedback by controlling queue depletion and the evacuation rate. Exposure is represented as a threshold transition activated by ASET. Fire growth and smoke-layer descent determine ASET and therefore influence exposure, but they are not affected by occupant movement. The model therefore represents dynamic coupling between fire-induced tenability loss and evacuation performance, rather than a bidirectional physical interaction between pedestrians and fire development.

2.3. Fire growth, smoke-layer descent, and ASET calculation

Fire-induced loss of tenability is represented using a simplified smoke-layer descent formulation. The evacuation zone is treated as a single compartment with floor area A_E and height H . Fire growth is described by a t^2 -type fire-growth coefficient, α , treated as an uncertain input variable. The relative smoke-layer height is calculated as:

$$\frac{z_L(t)}{H} = \left[1 + \frac{2k_v \alpha_{eff}^{1/3} t^{5/3}}{5(A_E/H^2)H^{4/3}} \right]^{-3/2} \quad (14)$$

where $z_L(t)$ is the smoke-layer height at time t , k_v is the entrainment coefficient, and α_{eff} is the effective fire-growth parameter. To account for smoke-model uncertainty, α_{eff} is defined as:

$$\alpha_{eff} = \alpha \varepsilon_s \quad (15)$$

where ε_s is a multiplicative uncertainty factor.

The onset of untenable conditions is defined by the smoke layer descending to the critical smoke-free height, z_{crit} . The Available Safe Egress Time is therefore:

$$ASET = \min \{ t : z_L(t) \leq z_{crit} \} \quad (16)$$

Since Eq. (14) is monotonic for a growing fire, ASET is obtained analytically by inverting the smoke-layer expression. Let:

$$B = \frac{2k_v \alpha_{eff}^{1/3}}{5(A_E/H^2)H^{4/3}} \quad (17)$$

Substituting $z_L(t) = z_{crit}$ into Eq. (14) gives:

$$ASET = \left[\frac{\left(\frac{z_{crit}}{H} \right)^{-2/3} - 1}{B} \right]^{3/5} \quad (18)$$

Equation (18) is evaluated independently for each stochastic realization. In this way, uncertainty in fire-growth rate, smoke-model uncertainty, enclosure geometry, and critical smoke-free height is propagated directly into the distribution of ASET.

The smoke-layer height criterion provides a transparent threshold for coupling fire development with evacuation progress. However, it does not explicitly account for toxic gas concentration, thermal exposure, radiant heat flux, or local visibility variations. Therefore, the calculated ASET is interpreted as a smoke-layer-based screening indicator of available evacuation time rather than as a complete tenability assessment.

2.4. Evacuation demand, exit capacity, queue formation, and RSET

The evacuation module estimates the time required for occupants to reach the exit system and the rate at which they are discharged through the available exits. The Required Safe Egress Time is decomposed into detection, recognition and response, travel, and queueing components:

$$RSET = t_{\text{det}} + t_{\text{resp}} + t_{\text{travel}} + t_{\text{queue}} \quad (19)$$

where t_{det} is the detection or warning time, t_{resp} is the recognition and response time, t_{travel} is the movement time to the exit system, and t_{queue} is the delay caused by congestion at the exits.

For alarm-based detection, the detection time is calculated as a function of fire growth and alarm delay (De Sanctis and Fontana, 2016):

$$t_{\text{det,alarm}} = 2.511 - 0.364 \log(\alpha_{\text{eff}}) + t_{\text{delay}} + \varepsilon_{\text{alarm}} \quad (20)$$

where t_{delay} is the additional alarm delay considered in the scenario analysis and $\varepsilon_{\text{alarm}}$ represents alarm-model uncertainty. For visual detection, the detection time is sampled from an exponential distribution:

$$t_{\text{det,visual}} \sim \text{Exp}(\lambda) \quad (21)$$

with:

$$\lambda = -\log(0.01) \sqrt{\frac{\alpha_{\text{eff}}}{50}} \quad (22)$$

The travel time is calculated from the characteristic travel distance and movement velocity:

$$t_{\text{travel}} = \frac{\sqrt{x^2 + y^2}}{v} \quad (23)$$

where x and y define the sampled initial location relative to the exit system and v is the movement velocity. In the aggregated SD formulation, these variables represent the characteristic travel condition of the occupant population in each stochastic realization.

The time at which occupants begin to arrive at the exit system is defined as:

$$t_{\text{start}} = \varepsilon_R (t_{\text{det}} + t_{\text{resp}} + t_{\text{travel}}) \quad (24)$$

where ε_R is a multiplicative uncertainty factor applied to the evacuation timing. Occupant arrivals are distributed around t_{start} over a finite arrival interval, avoiding the assumption that all occupants reach the exit simultaneously. The resulting arrival rate is denoted by $Q_{\text{arr}}(t)$.

Exit discharge is constrained by the total effective exit capacity:

$$C_{\text{exit}} = F_s W_{\text{tot}} \quad (25)$$

where F_s is the specific flow capacity and W_{tot} is the combined useable width of the exits. Queue formation is then governed by the difference between arrivals and discharge capacity:

$$\frac{dN_{\text{queue}}(t)}{dt} = Q_{\text{arr}}(t) - Q_{\text{evac}}(t) \quad (26)$$

with the evacuation flow calculated as:

$$Q_{\text{evac}}(t) = \min \left[\frac{N_{\text{queue}}(t)}{\Delta t}, C_{\text{exit}} \right] \quad (27)$$

Thus, queueing time is not prescribed independently, but emerges from the interaction between occupant arrivals and exit capacity.

For scenario comparison, two aggregate RSET indicators are used. $RSET_{95}$ represents the estimated time by which 95% of the initial occupants would be discharged through the exit system:

$$RSET_{95} = t_{\text{start}} + \frac{0.95N_0}{C_{\text{exit}}} \quad (28)$$

while $RSET_{100}$ represents the estimated full evacuation completion time:

$$RSET_{100} = t_{\text{start}} + \frac{N_0}{C_{\text{exit}}} \quad (29)$$

These indicators are compared with ASET to estimate the probability of incomplete evacuation before untenability. In the stock-flow simulation, the final classification of occupants is based on the number safely evacuated before ASET rather than on the deterministic RSET indicators alone.

2.5. Exposure endpoint, probabilistic indicators, and uncertainty propagation

Occupant consequence is evaluated using an exposure-based endpoint linked to the ASET/RSET criterion. Occupants are classified as safely evacuated if they leave the evacuation zone before ASET. Occupants still inside the zone when the smoke layer reaches the critical smoke-free height are classified as exposed to untenable conditions. The number of exposed occupants is therefore:

$$N_{\text{exp}} = N_0 - N_{\text{safe}}(\text{ASET}) \quad (30)$$

and the corresponding exposure fraction is:

$$f_{\text{exp}} = \frac{N_{\text{exp}}}{N_0} \quad (31)$$

This endpoint is conservative because it assumes that all occupants remaining inside at ASET are exposed, regardless of their exact location or subsequent movement. It is interpreted as a screening-level life-safety consequence indicator rather than as a direct fatality estimate.

The principal evacuation-failure indicator is the probability that the full evacuation time exceeds the available safe egress time:

$$P_{\text{fail}} = P(RSET_{100} > \text{ASET}) \quad (32)$$

A complementary indicator based on 95% evacuation completion is also considered:

$$P_{95} = P(RSET_{95} > \text{ASET}) \quad (33)$$

The expected exposure consequence is calculated over the stochastic ensemble as:

$$E[N_{\text{exp}}] = \frac{1}{N_s} \sum_{j=1}^{N_s} N_{\text{exp},j} \quad (34)$$

where N_s is the number of stochastic realizations. Threshold-based probabilities are also calculated to quantify non-negligible exposure:

$$P(N_{\text{exp}} > 1) \quad (35)$$

$$P(N_{\text{exp}} > 5) \quad (36)$$

$$P(f_{\text{exp}} > 0.01) \quad (37)$$

The evacuation safety margin is defined as:

$$M = RSET_{100} - \text{ASET} \quad (38)$$

Negative values indicate full evacuation before ASET, while positive values indicate incomplete evacuation before untenability.

The values in Table 1 define the probabilistic inputs used to generate the ensemble of model realizations. The output of each realization consists of ASET, RSET indicators, the time evolution of the occupant stocks, and the final number of safely evacuated and exposed occupants. These outputs are aggregated using ensemble means, percentiles,

Table 1

Probabilistic input variables used in the stochastic simulations (partially adapted from De Sanctis and Fontana, 2016).

Variable	Symbol	Distribution	Mean	Standard deviation/ bounds
Fire-growth rate	α	Lognormal	0.0236 kW/s ²	0.0300 kW/s ²
Critical smoke-free height	z_{crit}	Lognormal	1.80 m	0.16 m
Smoke-model uncertainty	ε_s	Normal, truncated positive	1.00	0.10
Occupant load density	ρ	Gamma	0.076 pers/m ²	0.068 pers/m ²
Alarm uncertainty	ε_{alarm}	Normal	0	0.32
Specific flow capacity	F_s	Normal, truncated positive	1.75 pers/s/m	0.11 pers/s/m
RSET uncertainty	ε_R	Lognormal	1.00	0.20
Recognition and response time	t_{resp}	Lognormal	32 s	16 s
Movement velocity	v	Weibull	1.34 m/s	0.16 m/s
Location coordinate	x	Uniform	—	$-\sqrt{2A_E}/2$ to $\sqrt{2A_E}/2$
Location coordinate	y	Uniform	—	0 to $\sqrt{2A_E}/2$

exceedance probabilities, and safety-margin distributions.

Uncertainty is introduced through probabilistic variables associated with fire development, smoke-layer descent, detection, occupant response, movement, and exit discharge. Fire-growth rate, critical smoke-free height, smoke-model uncertainty, recognition and response time, movement velocity, specific flow capacity, alarm uncertainty, and RSET uncertainty are sampled from predefined distributions. Initial occupant location is represented by sampled coordinates x and y , which determine the characteristic travel distance. For the reference near-critical case, the occupant density is set equal to its expected value to maintain a clearly defined initial population; stochastic occupant density can be considered in additional sensitivity analyses.

Sampling is performed using Latin Hypercube Sampling to improve coverage of the uncertain input space. A fixed random seed is used to support reproducibility, and common random samples are retained across scenario groups where possible. This ensures that differences among scenarios are mainly attributable to the varied design or operational parameter rather than to random sampling variability.

2.6. Numerical implementation, verification, and scenario design

The model is implemented in MATLAB using a discrete-time stock-flow simulation. For each stochastic realization, uncertain input variables are sampled, ASET is calculated analytically from the smoke-layer equation, and the occupant stocks are updated at each time step. The simulation tracks occupants remaining inside, occupants safely evacuated, queue accumulation, and occupants exposed to untenable conditions (Table 2).

The simulations are performed using $N_s = 10,000$ stochastic realizations, a fixed time step of $\Delta t = 1$ s, and a simulation horizon of 2400 s. Since ASET is calculated analytically, its value is not censored by the simulation horizon. The time horizon is used only to capture the evolution and stabilization of the stock-flow evacuation process.

Numerical verification is performed using occupant mass balance. For each realization, the following residual is evaluated:

$$\varepsilon_{MB}(t) = |N_0 - N_{in}(t) - N_{safe}(t) - N_{exp}(t)| \quad (39)$$

A zero or near-zero value of ε_{MB} confirms that occupants are neither

Table 2

Near-critical reference scenario parameters.

Parameter	Symbol	Value	Unit/description
Evacuation-zone area	A_E	3000	m ²
Enclosure height	H	2.5	m
Occupant load density	ρ	0.076	pers/m ²
Initial occupant population	N_0	228	persons
Number of representative exits	n_e	2	—
Width per exit	W_i	1.0	m
Total effective exit width	W_{tot}	2.0	m
Detection mode	—	Alarm	—
Additional alarm delay	t_{delay}	360	s
Fire-growth multiplier	—	1.5	Applied to sampled α
Number of stochastic realizations	N_s	10,000	—
Time step	Δt	1	s
Simulation horizon	—	2400	s

created nor lost during the simulation. Convergence is assessed by monitoring the stability of the expected number of exposed occupants, $E[N_{exp}]$, and the evacuation-failure probability, $P(RSET_{100} > ASET)$, as the number of stochastic realizations increases.

The framework is applied to a near-critical retail evacuation-zone scenario. The case represents an aggregated retail compartment or evacuation zone rather than an entire shopping mall. The reference scenario uses an evacuation-zone area of 3000 m², an enclosure height of 2.5 m, an occupant load density of 0.076 pers/m², and an initial population of:

$$N_0 = A_E \rho = 3000 \times 0.076 \approx 228 \quad (40)$$

The exit system consists of two representative exits, each with a useable width of 1.0 m, giving a total effective exit width of:

$$W_{tot} = 2.0 \text{ m} \quad (41)$$

The reference case assumes alarm-based detection with an additional alarm delay of 360 s. A fire-growth multiplier of 1.5 is applied to the sampled fire-growth rate to represent a near-critical fire-growth condition. This configuration is selected so that ASET and RSET are of similar magnitude, allowing the model to evaluate the transition between successful evacuation and exposure to untenable conditions.

Scenario analysis is performed by varying selected operational and design parameters around the reference configuration. The scenario groups include alarm delay, total effective exit width, enclosure height, enclosure area, fire-growth severity, and detection mode. Alarm delay and detection mode represent operational influences on evacuation initiation. Total effective exit width represents evacuation capacity. Enclosure height and area affect smoke-layer descent and available evacuation time. Fire-growth severity modifies the rate at which untenable conditions develop.

For each scenario, the full probabilistic simulation is repeated and the same output indicators are calculated. Scenario results are compared using expected exposed occupants, $P(RSET_{100} > ASET)$, threshold-based exposure probabilities, ASET and RSET distributions, and the safety-margin distribution.

3. Results and discussion

This section presents the numerical results obtained with the probabilistic System Dynamics framework. First, the stock-flow structure and mass-balance verification are summarized for the near-critical reference case. The reference case is then analyzed through the time evolution of occupant stocks, ASET/RSET distributions, and safety-margin indicators. Finally, scenario and sensitivity analyses are used to identify the dominant mechanisms controlling occupant exposure.

3.1. Reference case, stock-flow structure, and verification

The near-critical reference case was evaluated to verify the numerical consistency of the stock-flow formulation and to characterize the baseline level of evacuation safety before scenario analysis. The case represents a 3000 m² retail evacuation zone with a height of 2.5 m, a total effective exit width of 2.0 m, alarm-based detection, an additional alarm delay of 360 s, and an initial population of 228 occupants. This configuration was selected so that ASET and RSET are of similar magnitude, allowing the model to evaluate the transition between successful evacuation and exposure to untenable conditions.

Fig. 2 shows the stock-flow structure used to represent the evacuation process. Occupants are initially assigned to the stock N_{in} , representing occupants remaining inside the evacuation zone. Evacuation transfers occupants to N_{safe} , while occupants still inside when ASET is reached are transferred to N_{exp} . Queue formation and exit capacity regulate the evacuation flow. Fire growth and smoke-layer descent determine ASET, while detection, response, travel, and queueing determine evacuation progress and RSET-related indicators.

The numerical implementation was verified through occupant mass balance. For each stochastic realization, the model satisfies: $N_0 = N_{in}(t) + N_{safe}(t) + N_{exp}(t)$. The maximum mass-balance error was zero for the reference case, confirming that occupants are neither created nor

lost during the evacuation and exposure transitions.

The reference-case results (Table 3) confirm that the scenario is near-critical. The mean ASET is 648.96 s, while the mean $RSET_{100}$ is 666.72 s. The resulting mean safety margin is: $RSET_{100} - ASET = 17.77$ s. This slightly positive value indicates that, on average, full evacuation is not completed before untenable conditions occur. However, because the margin is small relative to the variability of fire and evacuation parameters, the final outcome is strongly influenced by uncertainty.

Table 3

Reference-case verification and outcome summary.

Metric	Value
Initial occupants, N_0	228
Mean ASET	648.96 s
Mean $RSET_{100}$	666.72 s
Mean safety margin, $RSET_{100} - ASET$	17.77 s
$P(RSET_{95} > ASET)$	0.5436
$P(RSET_{100} > ASET)$	0.5488
Mean safely evacuated occupants	131.74
Mean exposed occupants	96.26
$P(N_{exp} > 1)$	0.5979
$P(N_{exp} > 5)$	0.5550
Maximum mass-balance error	0

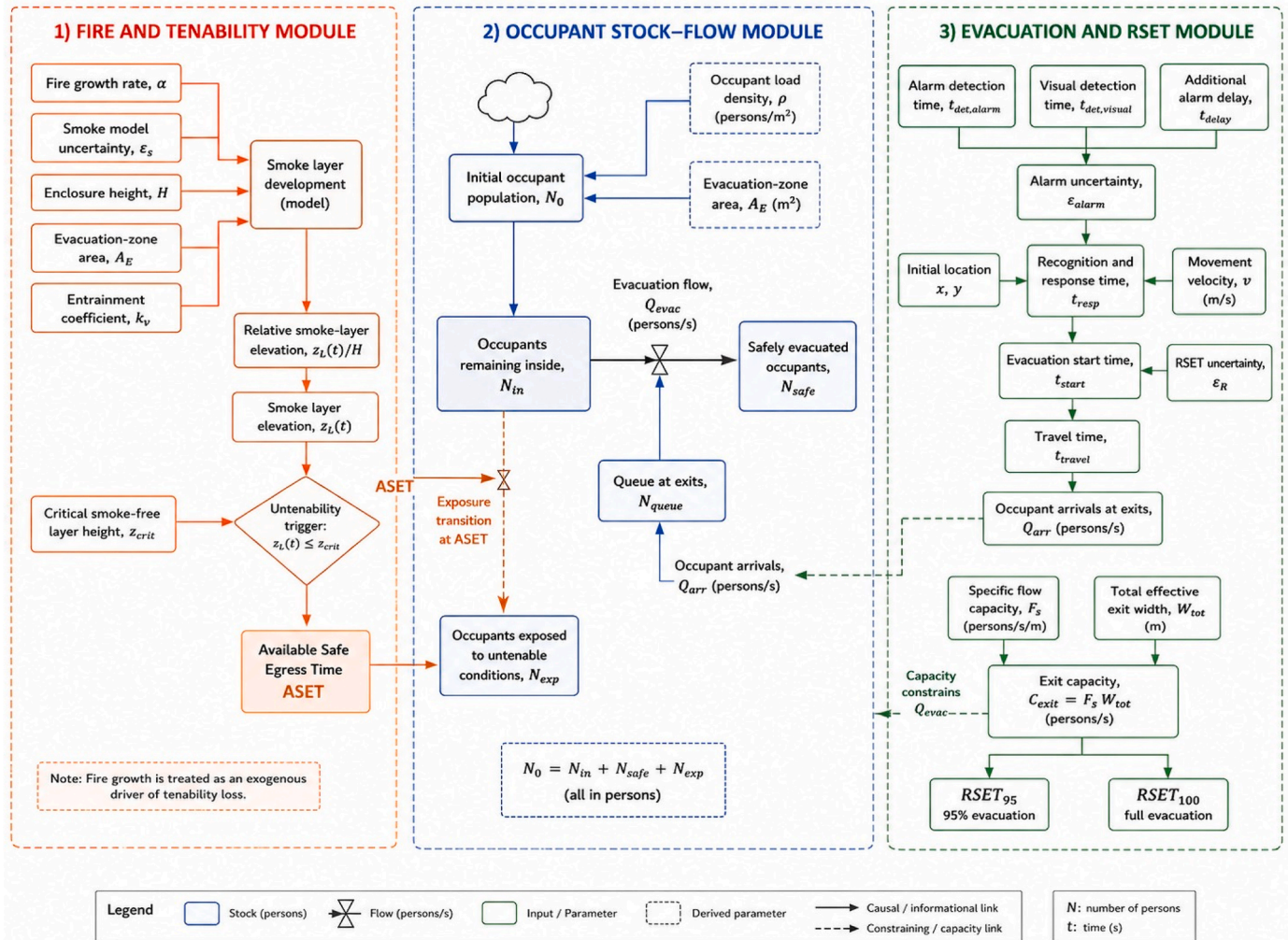


Fig. 2. System Dynamics stock-flow model for occupant exposure during fire growth and evacuation.

Note: Fire growth and smoke-layer descent determine ASET, while detection, response, travel time, queue formation, and exit capacity determine evacuation progress and RSET-related indicators. Occupants are represented through three stocks: occupants remaining inside, safely evacuated occupants, and occupants exposed to untenable conditions. Fire growth is treated as an exogenous driver of tenability loss; occupant movement does not feed back into fire development.

The probabilistic indicators show that $P(RSET_{100} > ASET) = 0.5488$, while $P(RSET_{95} > ASET) = 0.5436$. Thus, approximately half of the stochastic realizations lead to incomplete evacuation before untenability. The expected number of occupants safely evacuated before ASET is 131.74, while the expected number of occupants exposed to untenable conditions is 96.26. These results indicate that the reference case is neither trivially safe nor inevitably unsuccessful, but lies close to the transition between successful evacuation and exposure.

Overall, the reference case provides an appropriate basis for testing the probabilistic framework. Because ASET and RSET are close, moderate changes in detection delay, enclosure geometry, fire-growth severity, or evacuation capacity can shift the system toward either successful evacuation or significant exposure. This near-threshold behaviour is essential for demonstrating the value of probabilistic scenario analysis.

3.2. Dynamic evolution of occupant stocks

Fig. 3 shows the time evolution of the three main occupant stocks for the near-critical reference case: occupants remaining inside the evacuation zone, occupants safely evacuated before untenability, and occupants exposed to untenable conditions. The curves represent ensemble mean values over 10,000 stochastic realizations, with uncertainty bands showing the variability produced by the sampled fire and evacuation parameters.

At the beginning of the simulation, all 228 occupants are inside the evacuation zone. The number of safely evacuated occupants remains close to zero during the initial period because evacuation is delayed by detection, recognition and response, and travel time to the exit system. Once occupants begin to arrive at the exits, N_{safe} increases and N_{in} decreases according to the exit-capacity-limited evacuation flow.

The exposed-occupant curve increases progressively in the ensemble mean because ASET varies among stochastic realizations. In realizations with faster smoke-layer descent or more conservative tenability thresholds, untenability occurs earlier and a larger fraction of occupants is classified as exposed. In realizations with slower loss of tenability or faster evacuation, more occupants leave safely before ASET. This explains why the exposure curve does not rise at a single deterministic time.

By the end of the simulation, all occupants have been classified either as safely evacuated or exposed to untenable conditions. The mean final

values are 131.74 safely evacuated occupants and 96.26 exposed occupants. The wide uncertainty bands indicate that the same reference configuration can produce substantially different outcomes, ranging from nearly complete evacuation to large-scale exposure. This confirms that the reference case lies close to the boundary between successful and unsuccessful evacuation.

Overall, Fig. 3 illustrates the central dynamic mechanism represented by the model. Evacuation progressively reduces the population remaining inside, while fire-induced loss of tenability determines the time at which any remaining occupants are transferred to the exposed stock. The final consequence is therefore controlled by the relative timing of evacuation progress and ASET.

3.3. ASET, RSET, and safety-margin distributions

The probabilistic character of the near-critical reference case is shown in Fig. 4 through the distributions of ASET and $RSET_{100}$. The ASET distribution reflects uncertainty in fire-growth rate, smoke-layer modelling, and the critical smoke-free height, while the $RSET_{100}$ distribution reflects uncertainty in detection, response, travel, specific flow capacity, and aggregated evacuation timing.

The substantial overlap between the two distributions explains why the same reference configuration can lead to both successful and unsuccessful evacuation outcomes. When $RSET_{100} < ASET$, full evacuation is completed before untenability. When $RSET_{100} > ASET$, at least part of the population remains inside when untenable conditions occur and is classified as exposed.

For the reference case, the mean ASET is 648.96 s and the mean $RSET_{100}$ is 666.72 s. The mean safety margin is therefore slightly positive:

$M = RSET_{100} - ASET = 17.77$ s This indicates that, on average, full evacuation is marginally slower than the onset of untenability. However, the spread of the distributions is more informative than the mean values alone, because uncertainty shifts individual realizations to either side of the evacuation-failure threshold.

Fig. 5 shows the empirical cumulative distribution of the safety margin M . The vertical threshold at $M = 0$ separates successful full evacuation from incomplete evacuation before untenability. The fraction of realizations with positive M gives: $P(RSET_{100} > ASET) = 0.5488$. Thus, approximately 55% of the stochastic realizations lead to incomplete full evacuation before untenable conditions occur. This result

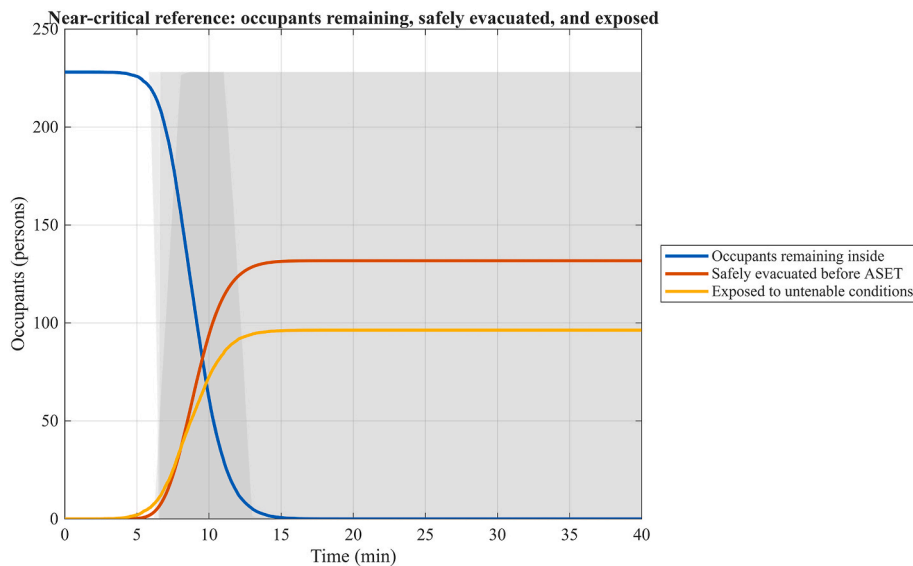


Fig. 3. Expected evolution of occupants remaining inside, safely evacuated, and exposed to untenable conditions for the near-critical reference case.

Note: Curves represent ensemble mean values obtained from 10,000 stochastic realizations. Shaded bands represent uncertainty intervals. Occupants are classified as exposed if they remain inside the evacuation zone when ASET is reached.

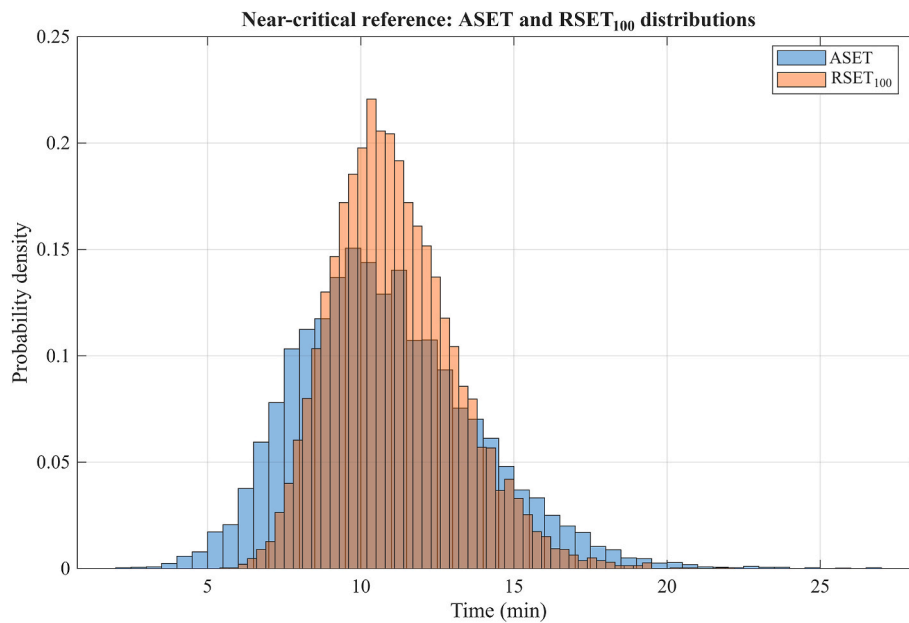


Fig. 4. Distributions of ASET and $RSET_{100}$ for the near-critical reference case.

Note: The overlap between the two distributions indicates the probability of incomplete evacuation before untenable conditions occur.

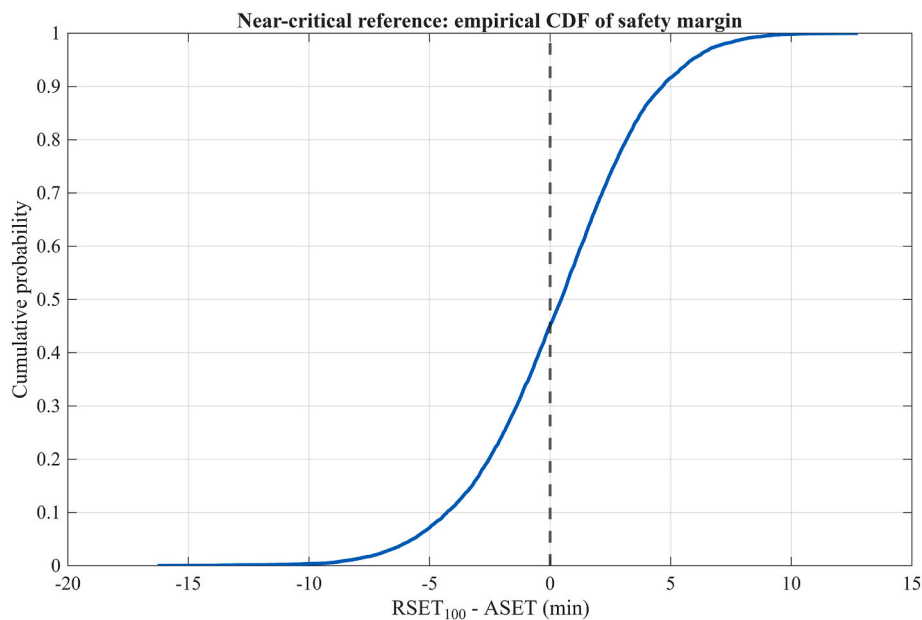


Fig. 5. Empirical cumulative distribution of the safety margin

Note: $M = RSET_{100} - ASET$. Negative values indicate full evacuation before ASET, while positive values indicate incomplete evacuation before untenability. The cumulative distribution at $M = 0$ defines the probability of successful full evacuation; the complementary probability is $P(RSET_{100} > ASET)$.

demonstrates why the model outputs are reported as probability distributions and exceedance probabilities, rather than only deterministic mean values.

The safety-margin distribution provides a compact indicator of the system state. Shifts of this distribution to the right indicate increasing exposure likelihood, caused by earlier loss of tenability or slower evacuation. Shifts to the left indicate improved evacuation safety, caused by delayed untenability or faster evacuation. The following scenario analyses are interpreted using this principle.

3.4. Influence of alarm delay

Alarm delay was varied from 0 to 720 s to evaluate how delayed evacuation initiation affects exposure in the near-critical reference configuration. Since the enclosure geometry, fire-growth conditions, occupant load, and exit capacity are unchanged in this scenario group, the ASET distribution remains the same. The observed changes are therefore mainly caused by the progressive shift of evacuation start time and $RSET_{100}$ toward later values.

Fig. 6 shows a strong monotonic increase in evacuation-failure and exposure probabilities as alarm delay increases. With no additional alarm delay, the probability of incomplete full evacuation is low:

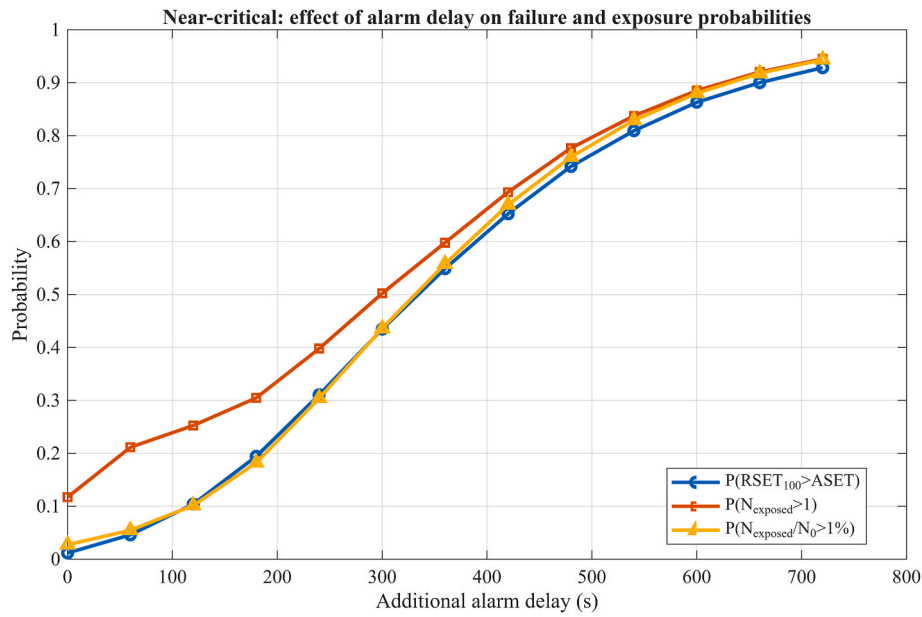


Fig. 6. Effect of additional alarm delay on evacuation-failure and exposure probabilities.

Note: Increasing alarm delay shifts evacuation initiation later while the ASET distribution remains unchanged, causing a monotonic increase in $P(RSET_{100} > ASET)$, $P(N_{\text{exp}} > 1)$, and $P(f_{\text{exp}} > 1\%)$.

$P(RSET_{100} > ASET) = 0.0117$ and the expected number of exposed occupants is only 1.18. At the reference delay of 360 s, the scenario becomes near-critical, with: $P(RSET_{100} > ASET) = 0.5488$ and $E[N_{\text{exp}}] = 96.26$.

When the additional delay reaches 720 s, the evacuation-failure probability increases to 0.9282, and the expected number of exposed occupants rises to 201.38, corresponding to most of the initial occupant population.

The same trend is observed for threshold-based exposure indicators. The probability of more than one exposed occupant increases from 0.1171 at zero delay to 0.9448 at 720 s, while $P(f_{\text{exp}} > 1\%)$ increases from 0.0273 to 0.9433. This indicates that alarm delay does not only

affect a small tail of the output distribution; it shifts the overall evacuation outcome from predominantly safe to predominantly unsuccessful.

The mechanism is direct: delaying alarm activation postpones occupant response and arrival at the exits, while smoke-layer descent continues. As a result, the safety-margin distribution shifts toward positive values, increasing the probability that occupants remain inside when ASET is reached. This identifies alarm delay as a dominant operational leverage point in the near-critical scenario. Reducing detection, alarm-transmission, and pre-movement delays can therefore produce substantial reductions in exposure risk.

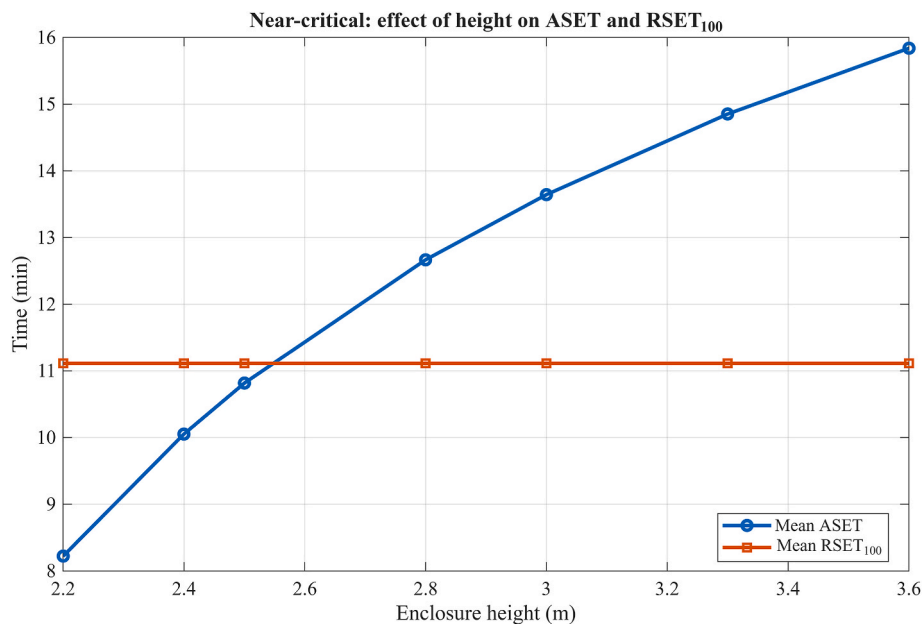


Fig. 7. Effect of enclosure height on mean ASET and $RSET_{100}$.

Note: Increasing enclosure height delays smoke-layer descent, increases ASET, and reduces the probability of incomplete evacuation before untenability.

3.5. Influence of enclosure height and fire-growth severity

Enclosure height and fire-growth severity primarily affect exposure by modifying ASET. They are therefore discussed together as fire-side drivers of the evacuation safety margin. In both scenario groups, the evacuation-zone layout, occupant load, alarm delay, and total effective exit width are kept unchanged, so changes in exposure are mainly caused by changes in smoke-layer descent.

Increasing enclosure height delays the descent of the smoke layer to the critical smoke-free height (see Fig. 7). As a result, mean ASET increases from 493.26 s at $H = 2.2$ m to 950.30 s at $H = 3.6$ m. Since mean $RSET_{100}$ remains approximately constant at 666.72 s, increasing height shifts the system from a condition dominated by evacuation failure to a more favourable condition. The probability of incomplete full evacuation decreases from 0.8055 to 0.1016, while the expected number of exposed occupants decreases from 160.68 to 14.30.

Fire-growth severity has the opposite effect (see Fig. 8). Increasing the fire-growth multiplier accelerates smoke-layer descent, reducing the time available for evacuation. When the multiplier increases from 0.5 to 4.0, mean ASET decreases from 808.42 s to 533.36 s. Over the same range, $P(RSET_{100} > ASET)$ increases from 0.3062 to 0.7601, and the expected number of exposed occupants increases from 49.02 to 143.90.

These results show that the fire-side parameters affect exposure by shifting the ASET distribution relative to the evacuation-time distribution. A taller enclosure increases the available time before untenability, while faster fire growth shortens it. In near-critical conditions, where ASET and RSET are close, these shifts produce large changes in exposure probability. This confirms that evacuation performance cannot be interpreted independently from the rate of tenability loss.

From a design and loss-prevention perspective, the results indicate that measures delaying untenability can be highly effective in reducing exposure. Such measures may include increasing the effective smoke reservoir, improving smoke management, limiting fire-growth severity, or controlling fuel contribution. Their benefit is especially relevant when evacuation delay cannot be fully eliminated.

3.6. Secondary scenario effects: exit width, enclosure area, and detection mode

The effects of total effective exit width, enclosure area, and detection mode were also evaluated to examine additional design and operational influences on the ASET/RSET balance (Table 4). These parameters affect exposure through different mechanisms: exit width modifies evacuation capacity, enclosure area affects both occupant load and smoke-layer descent, and detection mode changes the time at which evacuation begins.

Increasing the total effective exit width reduces $RSET_{100}$ and lowers the probability of incomplete full evacuation. When W_{tot} increases from 1.0 to 5.0 m, mean $RSET_{100}$ decreases from 732.12 to 627.48 s, while $P(RSET_{100} > ASET)$ decreases from 0.6681 to 0.4766. This confirms that exit capacity influences evacuation completion. However, the expected number of exposed occupants changes only slightly once a minimum effective width is available. In the near-critical reference configuration, this indicates that delayed evacuation initiation is a stronger bottleneck than discharge capacity. Therefore, increasing exit capacity alone may provide limited additional benefit if warning and response delays remain large.

The enclosure-area scenarios show a competing effect. Increasing the area from 2000 to 6000 m² increases the initial occupant population from 152 to 456 occupants, but it also increases mean ASET from 508.82 to 983.63 s because the smoke layer descends more slowly in the larger volume. In the investigated range, the increase in available evacuation time dominates the increase in occupant load, causing the expected number of exposed occupants to decrease from 105.10 to 41.74. This result should not be generalized as meaning that larger enclosures are inherently safer; rather, it highlights the need to evaluate geometric parameters through their simultaneous influence on both evacuation demand and tenability development.

The detection-mode comparison illustrates the importance of evacuation initiation time. Under the delayed alarm condition used in the reference case, the mean evacuation-start time is 601.32 s, mean $RSET_{100}$ is 666.72 s, and the expected number of exposed occupants is 96.26. Under the visual-detection model, the mean evacuation-start time decreases to 65.98 s and mean $RSET_{100}$ decreases to 131.38 s,

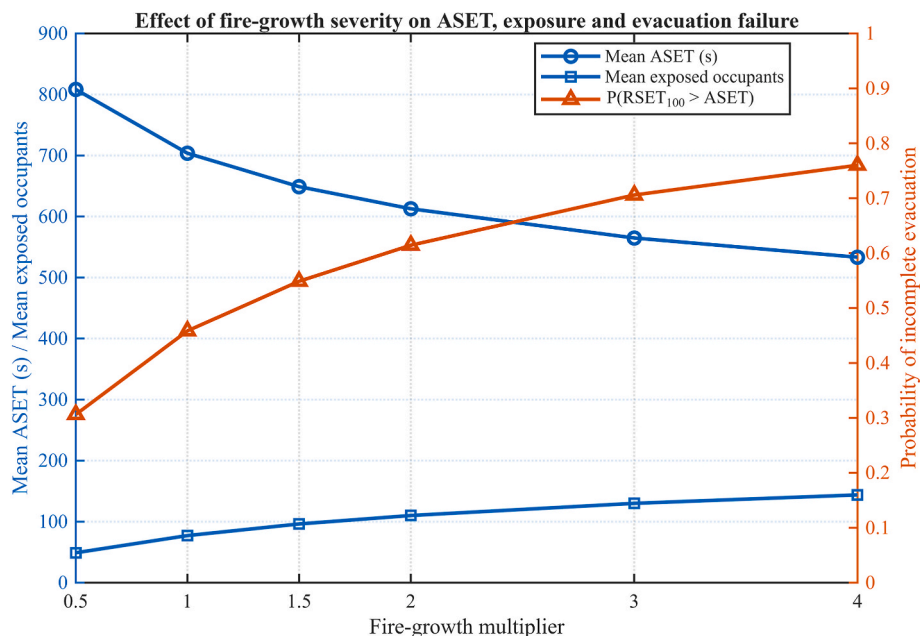


Fig. 8. Effect of fire-growth severity on mean ASET, expected exposed occupants, and evacuation-failure probability.

Note: Increasing fire-growth severity accelerates smoke-layer descent, reduces ASET, and increases both the expected number of exposed occupants and the probability that $RSET_{100}$ exceeds ASET.

Table 4

Selected secondary scenario outcomes for exit width, enclosure area, and detection mode.

Scenario group	Parameter value	Mean ASET (s)	Mean $RSET_{100}$ (s)	Mean exposed occupants	$P(RSET_{100} > ASET)$
Total effective exit width	$W_{tot} = 1.0$ m	648.96	732.12	97.05	0.6681
Total effective exit width	$W_{tot} = 2.0$ m	648.96	666.72	96.26	0.5488
Total effective exit width	$W_{tot} = 5.0$ m	648.96	627.48	96.26	0.4766
Enclosure area	$A_E = 2000$ m ²	508.82	640.80	105.10	0.7757
Enclosure area	$A_E = 3000$ m ²	648.96	666.72	96.26	0.5488
Enclosure area	$A_E = 6000$ m ²	983.63	741.42	41.74	0.1989
Detection mode	Alarm detection	648.96	666.72	96.26	0.5488
Detection mode	Visual detection	648.96	131.38	0.073	0.0000

reducing expected exposure to 0.073 occupants. This result does not imply that visual detection is generally preferable to alarm detection. Instead, it shows that the timing of detection and warning strongly controls the safety margin. A reliable alarm system with minimal delay would produce the same type of favourable shift toward successful evacuation.

Overall, these secondary scenarios support the main interpretation of the model. Exposure is governed by the relative timing of evacuation progress and loss of tenability. Parameters that delay evacuation initiation or accelerate untenability shift the safety margin toward failure, while parameters that increase available time or reduce required evacuation time shift it toward successful evacuation. In the present near-critical case, early warning and fire-side tenability parameters are more influential than additional exit width beyond a minimum effective capacity.

3.7. Global sensitivity analysis

A global sensitivity analysis was performed using Spearman rank-correlation coefficients between uncertain input variables and two output quantities: the final number of exposed occupants, N_{exp} , and the safety margin, $M = RSET_{100} - ASET$. This analysis identifies which uncertain parameters most strongly influence exposure in the near-critical reference case.

The final number of exposed occupants is most strongly correlated with the RSET uncertainty factor, the critical smoke-free layer height, and the fire-growth rate. The corresponding Spearman coefficients are 0.508, 0.485, and 0.473, respectively. The same variables also dominate the safety margin, with correlations of 0.569, 0.550, and 0.545. These results confirm that exposure is controlled by both evacuation-side uncertainty and fire-side uncertainty.

The positive correlation with fire-growth rate is consistent with the smoke-layer descent model: faster fire growth reduces ASET and increases the probability that occupants remain inside when untenability occurs. The positive correlation with critical smoke-free height reflects the fact that a higher tenability threshold causes untenability to be reached earlier. The strong influence of the RSET uncertainty factor indicates that aggregated uncertainty in detection, response, travel, and evacuation timing substantially affects the final exposure outcome.

Other variables show weaker correlations in the reference case. Response time and smoke-model uncertainty have small positive effects, while movement velocity has a weak negative effect, as expected. Specific flow capacity has little correlation with final exposed occupants in this scenario, supporting the result that exit capacity is not the dominant bottleneck once a minimum effective width is available. The initial occupant population was fixed in the reference case; therefore, no rank-correlation coefficient is reported for this variable.

Overall, the sensitivity analysis supports the scenario findings. The dominant drivers are those that shift either ASET or RSET and therefore move the safety-margin distribution toward or away from the evacuation-failure threshold. This confirms the usefulness of the framework for identifying which parameters require careful characterization in more detailed fire-safety assessments.

3.8. Discussion, implications, and limitations

The results show that occupant exposure is governed by the relative timing of two competing processes: evacuation progress and fire-induced loss of tenability. Parameters that delay evacuation or accelerate smoke-layer descent shift the safety margin $M = RSET_{100} - ASET$ toward positive values, increasing the probability of incomplete evacuation before untenability. Conversely, parameters that increase ASET or reduce RSET shift the system toward successful evacuation.

Among the investigated variables, alarm delay produced one of the strongest effects. Increasing the additional alarm delay moved the system from a mostly successful evacuation condition to a high-exposure condition. This indicates that early warning, alarm reliability, occupant response, and pre-movement behaviour can be decisive in near-critical scenarios. From a loss-prevention perspective, measures that reduce detection and response delays may provide substantial benefit, particularly when ASET and RSET are close.

Fire-side parameters also strongly influenced exposure. Enclosure height increased ASET by delaying smoke-layer descent, while higher fire-growth severity reduced ASET and increased exposure. These results emphasize that evacuation performance should not be assessed independently from fire development. A design that appears acceptable under one fire-growth assumption may become near-critical or unsafe under faster fire growth or more conservative tenability thresholds.

The total effective exit width affected evacuation completion time and reduced the probability that $RSET_{100}$ exceeded ASET. However, in the reference configuration, increasing exit width beyond a minimum effective capacity produced a smaller reduction in expected exposure than reducing alarm delay or increasing ASET. This suggests that the dominant bottleneck depends on the scenario. In the near-critical case considered here, delayed evacuation initiation was more influential than discharge capacity once a basic exit capacity was available.

The enclosure-area results illustrate the importance of considering competing mechanisms. Increasing area increased the number of occupants, but it also delayed smoke-layer descent in the adopted smoke-layer formulation. In the investigated range, the increase in ASET dominated the increase in evacuation demand. This result should be interpreted as scenario-specific, not as a general conclusion that larger spaces are safer. It demonstrates why integrated fire-evacuation modelling is useful: the same parameter can influence both available and required evacuation time.

The framework is therefore most useful as a screening and prioritization tool. It can identify near-critical configurations, rank influential parameters, compare design and operational alternatives, and select scenarios that require detailed analysis using higher-resolution fire or evacuation models. The approach is particularly useful when many scenarios must be explored rapidly before selecting a smaller subset for detailed simulation.

Some limitations should be considered when interpreting the results. First, the fire model uses a simplified smoke-layer descent criterion, and untenability is defined only by the smoke layer reaching a critical smoke-free height. Toxic gas concentration, fractional effective dose, thermal exposure, radiant heat flux, and local visibility are not explicitly represented. Second, occupants are modelled as an aggregated

population, so individual trajectories, local density variations, route choice, social influence, and adaptive behaviour are not resolved. Third, the exit system is represented through total effective exit width and specific flow capacity, without modelling detailed exit distribution, uneven exit choice, merging flows, or local bottlenecks.

In addition, fire growth is treated as an uncertain exogenous driver of tenability loss. Occupant movement does not feed back into fire development, ventilation, door opening, suppression, or fuel conditions. The model therefore represents dynamic coupling between fire-induced tenability loss and evacuation performance, but not a fully bidirectional physical interaction between pedestrians and fire. Finally, the exposure endpoint should not be interpreted as a direct fatality estimate. Occupants remaining inside at ASET are classified as exposed to untenable conditions, but no vulnerability or dose-response model is used to estimate injury or fatality probability.

Despite these limitations, the framework provides a transparent way to examine the probabilistic competition between ASET and RSET. It supports early-stage fire safety analysis by identifying when exposure is driven mainly by delayed warning, fire-growth severity, tenability thresholds, evacuation uncertainty, or exit capacity. Cases found to be highly sensitive or close to the evacuation-failure threshold should be further investigated using detailed fire modelling, evacuation simulation, experimental data, or project-specific calibration where available.

4. Conclusions

This study developed a probabilistic System Dynamics framework for screening-level assessment of occupant exposure during fire growth and evacuation. The model integrates smoke-layer descent, ASET calculation, evacuation timing, exit-flow capacity, queue formation, and stochastic uncertainty within a stock-flow structure. The framework distinguishes occupants remaining inside the evacuation zone, occupants safely evacuated before untenability, and occupants exposed to untenable conditions.

A major feature of the approach is the explicit comparison between ASET and evacuation progress. ASET is calculated from the smoke-layer descent model, while RSET-related indicators are obtained from detection, response, travel, and exit-capacity components. Occupants not safely evacuated by the onset of untenable conditions are classified as exposed. This exposure-based endpoint provides a transparent consequence measure without requiring an unsupported fatality-vulnerability model.

The near-critical reference scenario demonstrated the value of the probabilistic formulation. For the reference case, the mean ASET was 648.96 s and the mean $RSET_{100}$ was 666.72 s, giving a mean safety margin of 17.77 s. The probability that $RSET_{100}$ exceeded ASET was 0.5488, and the expected number of exposed occupants was 96.26 out of an initial population of 228. These results show that the scenario lies close to the transition between successful evacuation and exposure, where uncertainty strongly affects the final outcome.

The scenario analysis identified alarm delay as a dominant operational driver. Increasing the additional alarm delay from 0 to 720 s increased $P(RSET_{100} > ASET)$ from 0.0117 to 0.9282, while the expected number of exposed occupants increased from 1.18 to 201.38. This result highlights the importance of reducing detection, warning, and pre-movement delays in near-critical fire scenarios.

Fire-side parameters also had a strong influence on exposure. Increasing enclosure height from 2.2 to 3.6 m increased mean ASET from 493.26 to 950.30 s and reduced the expected number of exposed occupants from 160.68 to 14.30. Conversely, increasing the fire-growth multiplier from 0.5 to 4.0 decreased mean ASET from 808.42 to 533.36 s and increased expected exposure from 49.02 to 143.90 occupants. These results confirm that evacuation safety depends on the coupled timing of fire-induced tenability loss and occupant movement.

The total effective exit width influenced the evacuation completion time and the probability that $RSET_{100}$ exceeded ASET. However, in the

near-critical reference case, its effect on expected exposure was weaker than that of alarm delay, enclosure height, and fire-growth severity. This indicates that, once a minimum exit capacity is available, delayed evacuation initiation can dominate the exposure outcome. The result emphasizes that geometric capacity improvements and operational measures should be evaluated together rather than independently.

The sensitivity analysis supported the scenario findings. The final number of exposed occupants was most strongly correlated with RSET uncertainty, critical smoke-free layer height, and fire-growth rate. These variables also dominated the safety-margin distribution. The results therefore show that both evacuation-side uncertainty and fire-side uncertainty must be considered when evaluating life-safety performance in near-critical conditions.

The proposed framework is not intended to replace detailed CFD or agent-based evacuation modelling. The fire model uses a simplified smoke-layer criterion, occupants are represented as an aggregated population, and the exposure endpoint does not represent direct fatality probability. Instead, the framework is best interpreted as a probabilistic screening and decision-support tool. It can identify near-critical scenarios, rank influential parameters, compare design and operational alternatives, and select cases that require more detailed analysis.

Future work should extend the framework by incorporating additional tenability criteria, such as toxic gas concentration, visibility, thermal exposure, and fractional effective dose. Further developments could also include coupling with higher-resolution evacuation models, explicit behavioural adaptation, multi-zone smoke movement, suppression effects, and validated vulnerability models for estimating injury or fatality probability. Experimental data, benchmark cases, or comparisons with established fire and evacuation tools would further strengthen calibration and validation.

Overall, the study shows that System Dynamics can provide a useful structure for representing the time-dependent interaction between fire development, evacuation performance, and uncertainty. By focusing on probabilistic ASET/RSET competition and exposure to untenable conditions, the framework supports more transparent and risk-informed screening of fire-evacuation scenarios.

CRedit authorship contribution statement

Julio Ariel Dueñas Santana: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ruben Van Coile:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Almerinda Di Benedetto:** Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Ernesto Salzano:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jlp.2026.106098>.

Data availability

Data will be made available on request.

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