SPECIAL MOBILITY STRAND

PERFORMANCE-BASED FIRE SAFETY ENGINEERING

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Technical University of Denmark (DTU), Department of Civil Engineering

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Performance-based Fire-safety Engineering

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Performance-based Fire-safety Engineering

Grenfell tower, UK

Notre Dame, Paris

The society don`t like fires with loss of human lives (Grenfell) or loss of huge values, national symbols (Notre Dame)!

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Procedure

Ref. (Sørensen 2014)

Often used procedure in Fire-safety Engineering

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Procedure

Table 6.2. Overall contents for fire-safety engineering.

Overall contents of fire-safety engineering
1. Fire strategy report:
• Presentation of the basis for fire safety (building presentation).
• Selection of fire safety level in the form of acceptance criteria.
• Suggestion of fire solutions (based on calculations).
2. Fire analysis:
• Analysis of the building's total evacuation time (result presentation).
• Analysis of critical times in relation to the parameters where acceptance criteria is set (result presentation).
• Determination of how good/bad the various proposed fire solutions are.
3. Comparison:
• Fire solution's performance versus fire requirements (results versus acceptance criteria).
• Assessment of whether the fire solution satisfies the fire strategy's requirements.
4. Reporting:
• Preparation of a so-called fire manual, which summarizes the above points and the operating instructions, whereby all fire-safety documentation for the building is gathered in one place.

Ref. (Sørensen 2014)

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Fire strategy

- Description of building
- Application category
- Fire scenarios
- Acceptance criteria
- Solutions (passive and active)

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Fire-safety

$t_{evac} < t_{crit}$

where

t_{evac} is the sum of warning, reaction/decistion and walking time

t_{crit} is the time until critical conditions (temp, radiation, vis, smoke etc.)

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Fire scenarios

Who and how to establish fire scenarios for a building?

- No fire means no critical conditions
- We do not know if, where and when a fire arise in a building
- We do not know the size of a future fire

All these unknowns lead us to utilize risk analysis.

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Fire scenarios

Risk approach:

Select fire scenarios among these:

1. Fires that happen with a certain high probability
2. Fires that posses a high risk level

Risk level = consequense · probability

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Fire scenarios

A fire scenario is a fire cycle characterized by:

- a specific initial fire (fire-site, ignition source, fire object)
- the further fire cycle (energy release-time curve indicating the maximum energy release rate)
- smoke and fire spread, including the position of doors (open or closed)
- other matters of importance for fire development, cycle and extinction

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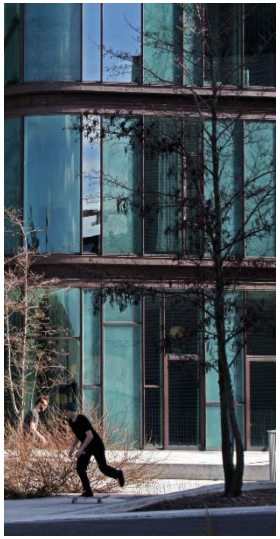
Acceptance criteria

t_{crit} is the time until critical conditions appears. Therefore, we need some acceptance criteria to judge if or when critical conditions arise.

Temperature
Visibility
Radiation
Smoke (height)
Oxygen level
Toxicity



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Acceptance criteria

Temperature (inhalation)

Table 6.6. Acceptance criteria for inhalation temperature. * Temperature is measured 2 m above floor level if there exists a 2-zone air stratification in the room.

Factor	Acceptance criteria	Remarks
Temperature below the smoke layer * (inhaling temperature), T_{inh}	$T_{inh} \leq -36.6 \ln\left(\frac{t_m}{179}\right)$	Inverse formula: $t_m \leq 179 \cdot e^{-T_{inh}/36.6}$
	$T_{inh} \leq 60^{\circ}C$	

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Acceptance criteria

Optical density (visibility-requirement)

Table 6.4. Acceptance criteria for optical density (visibility). Large rooms have an area > 150 m^2.

Condition	Acceptance Criterion	Comments
Optical density, OD, in small rooms	OD < 3.33 dB/m OD < 2.00 dB/m	 When the room is part of an escape route
Optical density, OD, in large rooms	OD < 1.25 dB/m OD < 0.83 dB/m	 When the room is part of an escape route

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Acceptance criteria

Radiation

Table 6.5. Acceptance criteria for radiation.

Condition	Acceptance Criterion	Comments
Radiation intensity, q	$q \leq 10\ kW/m^2$	Maximum of 4 seconds
Radiation dose, qt	$qt \leq 40\ kWs/m^2 = 40\ kJ/m^2$	when q is larger than $1.5\ kW/m^2$ and less than $10\ kW/m^2$
Radiation intensity, q	$q \leq 1.5\ kW/m^2$	Tolerated throughout the evacuation time

Thermal radiation plays an equally important role in fire spread, and this is discussed later

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Acceptance criteria

Smoke (free height above floor)

Table 6.7. Acceptance criterion for smoke-free height above floor level.

Factor	Accept criterion
Smoke-free height above floor level, H_{∞}	$H_{\infty} \geq 1{,}6 \text{ m} + 0{,}1 \cdot H$

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Acceptance criteria

Oxygen (min. level)

Table 6.8. Acceptance criterion for the oxygen concentration of inhaled air.

Factor	Accept criterion
Oxygen concentration, C_{oxygen}	$C_{oxygen} \geq 16\%$

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Acceptance criteria

Toxicity (gases that could be present in a fire)

Table 6.9. Occurrences of gases and impact on people.

Gas	Source materials at fire site	Effects on humans
Carbon monoxide (CO)	organic material, always occurs	Binds to the blood at the expense of oxygen (O_2)
Carbon dioxide (CO_2)	organic material, always occurs	Increases breathing rate
Nitrous gases (NO og NO_2)	ammonia, NPK fertilizer, plastic products (e.g. polyamide)	Can cause difficulty breathing and pulmonary oedema
Sulphur dioxide (SO_2)	sulphur vulcanized rubber products (e.g. car tires)	Can cause acute pulmonary oedema
Hydrogen cyanide (HCN)	plastic products (e.g. polyurethane)	Impaired sense of smell, convulsions and unconsciousness. Can be fatal after only a few minutes
Hydrogen chloride (HCl)	plastic products (e.g. PVC and Neoprene)	Acute pulmonary oedema

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Acceptance criteria

Toxicity

Table 6.10. Acceptance criteria for concentrations of toxic fumes.

Factor	Acceptance criteria	Remarks
CO concentration, C_{CO}	$C_{CO} \leq 0.10\%$	*
CO_2 concentration, C_{CO2}	$C_{CO2} \leq 4.0\%$	*
HCN concentration, C_{HCN}	$C_{HCN} \leq 0.005\%$	*
SO_2 concentration, C_{SO2}	$C_{SO2} \leq 0.003\%$	*
NO_2 concentration, C_{NO2}	$C_{NO2} \leq 0.002\%$	*
HCl concentration, C_{HCl}	$C_{HCl} \leq 0.10\%$	*
HBr concentration, C_{HBr}	$C_{HBr} \leq 0.02\%$	*
HF concentration, C_{HF}	$C_{HF} \leq 0.012\%$	*
Acrolein concentration, $C_{acrolein}$	$C_{acrolein} \leq 0.0002\%$	*

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Acceptance criteria

Toxicity

*: The total exposure is the sum of the concentrations present and their associated doses [BSI]. The limit of human tolerance is thus estimated from the amount of the various gases present critical dose, i.e. concentration (%) • exposure time (min).

FID = (CO dose/1.5) + (CO_2 dose/25) + (O_2 emptying dose/45) + (HCN dose/0.05)

FIC = (SO_2 conc./0.003) + (NO_2 conc./0.002) + (HCl conc./0.1) + (HBr conc./0.02) + (HF conc./0.012) + (acrolein conc./0.0002).

If FID = 1 or FIC = 1, the tolerance limit is exceeded and people exposed to that particular combination of effects will lose consciousness.

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Acceptance criteria

Fire spread to other rooms

Table 6.11. Acceptance criteria for fire spread to other rooms in the building.

Factor	Acceptance criteria	Remarks
Radiation intensity, q	$q \leq 20\ kW/m^2$	Radiation intensity on the floor
Temperature in the smoke layer, T_g	$T_g \leq 500°C = 773\ K$	The limit is set around 600°C
Temperature on the unexposed side of the building elements (wall, ceiling, floor)	Mean temperature $T_{covered} \leq 160°C$	However, maximum 200°C at single points

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Acceptance criteria

Fire spread to other buildings

Table 6.12. Acceptance criteria for fire spreading to other buildings.

Factor	Acceptance criteria	Remarks
Radiation intensity, q	$q \leq 15$ kW/m^2 in boundary of premises	Exposure time t = 0 to 30 min.
Radiation intensity, q	$q \leq 20$ kW/m^2 in boundary of premises	At any time

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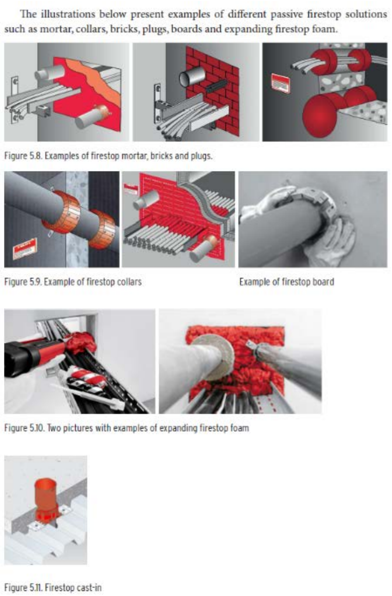
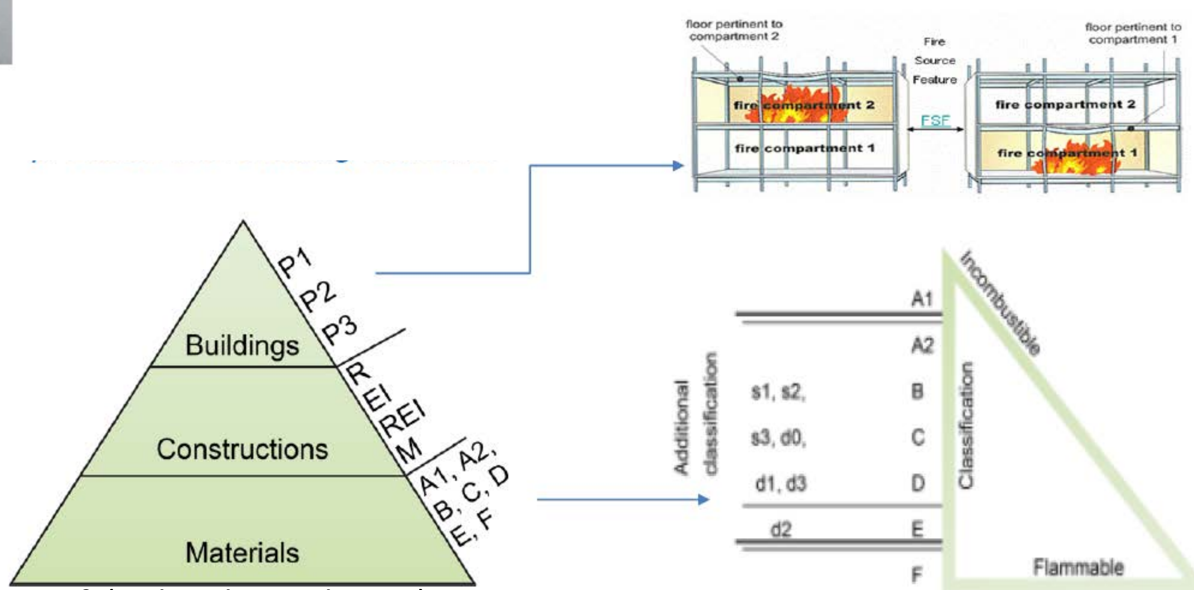
Solutions



Ref. (Sørensen 2014)

Requirements for elements and construction products are laid down in a Commission Decision in the standard EN 13501-1 "Fire classification of construction products and building elements"



Ref. (Dubravka et al 2017)

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Solutions - Passive and active fire-safety measures

Passive protection	Active protection
Fire wall	Warning system
Fire door	Aut. Fire Alarm system (AFA)
Fire compartment	Aut. Water Sprinkler System (AWS)
Fire section	Aut. Smoke Ventilation (ASV)
Fire stop (around pipes etc.)	Aut. Compartment Extinguishing (ACE)
Fire paint (fx steel)	Smoke detector
Cladding (gypsum etc.)	Flame detector

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Solutions - Passive protection (example)

Protection of structural steel is also a very important issue in order to ensure stability during a fire. Some different methods are shown in the figure below.

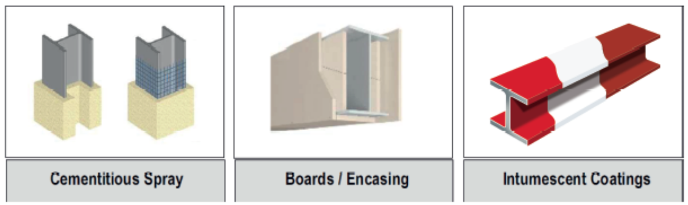

Figure 5.1. Examples of structural steel protection

The principle of the intumescent coating is shown in the figure below, presented through a 4-stage fire exposure process.

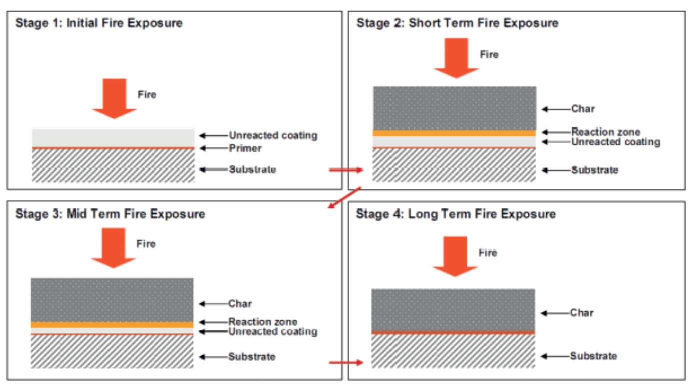

Figure 5.2. Structural steel protection. A char layer is developed and protects the steel from the heat.

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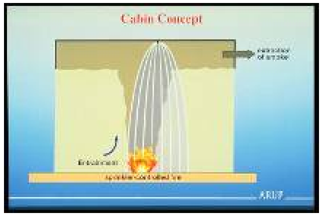
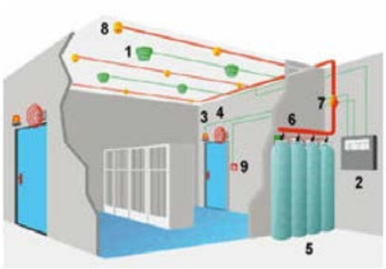
Solutions (active fire protection)





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Analysis - evacuation

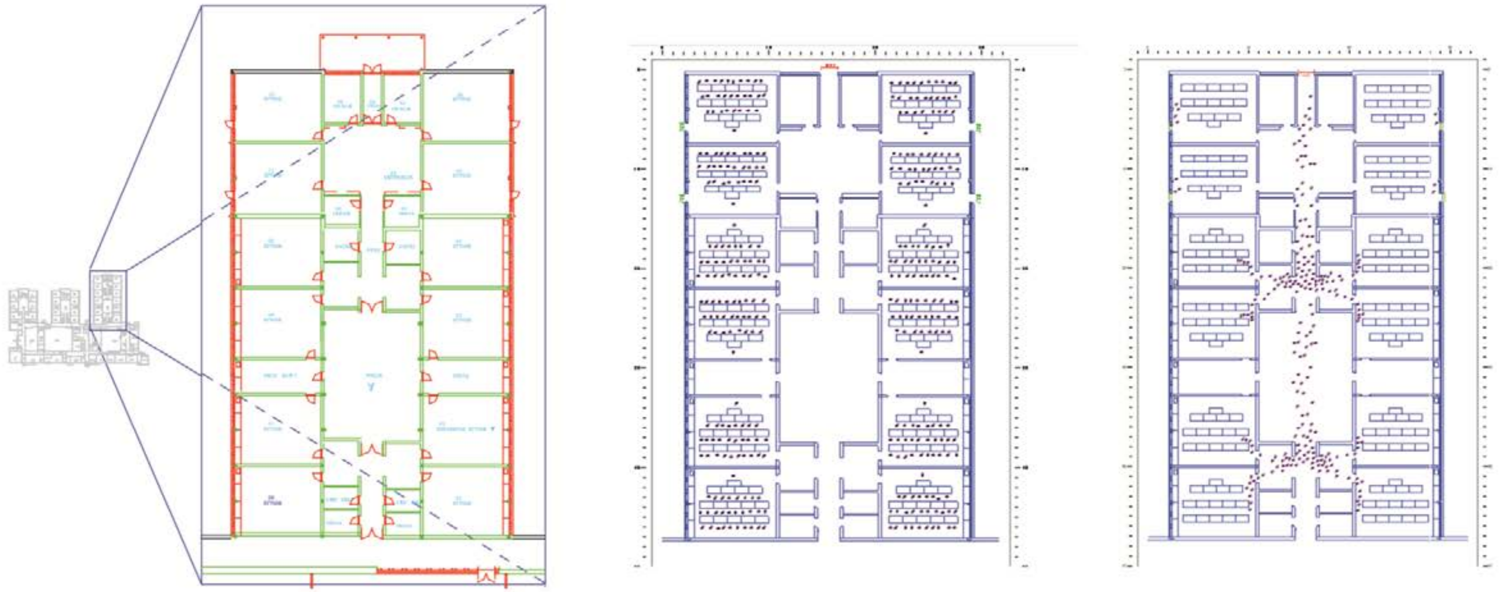

Figure 17.5. Modelling of evacuation in Simulex. You can use a CAD model (plan view) as an input file (left picture) and apply persons, exits, etc. (middle picture). To the right is a picture from the animation of the evacuation.

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Analysis – fire physics (acceptance criteria)

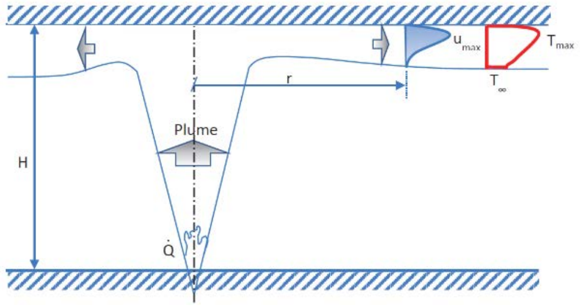
$$\Delta T_0 = \left(\frac{\kappa}{0.9\cdot\sqrt{2g}}\right)^2 \cdot \left(\frac{z}{\dot{Q}^{2/5}}\right)^{2\eta-1} \cdot T_\infty \qquad (11.29)$$

$(T_\infty = 293)$

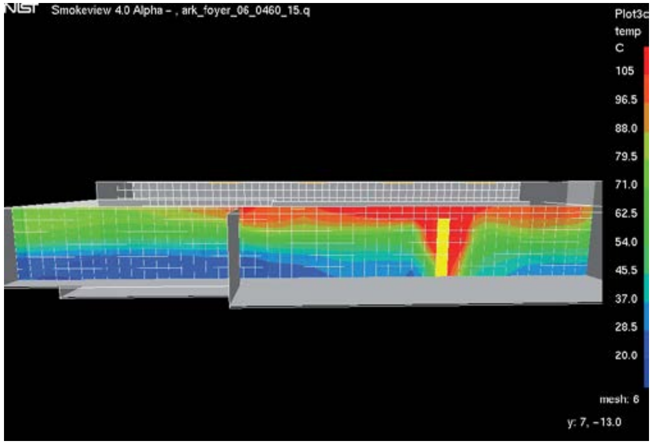
$$u_0 = \kappa \cdot \left(\frac{z}{\dot{Q}^{2/5}}\right)^{\eta} \cdot \dot{Q}^{1/5} \qquad (11.30)$$

where the constants η and κ will vary depending on the three regions, so that:

Region	$z/\dot{Q}^{2/5}\left[m/kW^{2/5}\right]$	η	κ
Continuous flame	< 0.08	½	6.8 ($m^{1/2}/s$)
Intermittent flame	0.08 to 0.2	0	1.9 [$m/(kW^{1/5}s)$]
Buoyant plume	> 0.2	- ⅓	1.1 [$m^{4/4}/(kW^{1/3}s)$]



Ref. (Sørensen 2014)



Rate of increase of Φ in the fluid element	+	Net rate of Φ flow out of the fluid element	=	Rate of increase of Φ caused by diffusion	+	Rate of increase of Φ caused by "sources"

Using Gauss' divergence theory, $\int_{cv} div\, \underline{a} dV = \int_A \underline{n}\cdot \underline{a} dA$ (cv: control volume), (19.28)

can be integrated over volume and time, giving a general integral form of the transport equation:

$$\int_{\Delta t} \frac{\partial}{\partial t}\left(\int_{cv}(\rho\Phi)dv\right)dt + \int_{\Delta t}\int_{A} \underline{n}\cdot(\rho\Phi\underline{u})dA\cdot dt = \int_{\Delta t}\int_{n} n\cdot(\Gamma_\Phi \cdot grad\Phi)dA\cdot dt + \int_{\Delta t}\int_{cv} S_\Phi \cdot dv\cdot dt \qquad (19.29)$$

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Comparement

$t_{evac} < t_{crit}$

Is this fulfilled for all fire scenarios
and for all acceptance criteria ?

If so, collect all documentation
If not, make another fire solution

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Sensitivity analysis

$$\Delta t = t_{evac} - t_{crit} \qquad (18.3)$$

This value must be less than zero in order to proceed with the calculation procedure. In other words:

$$\Delta t < 0$$

If $|\Delta t|$ is small, a risk analysis should be performed, since a small numerical value indicates that even the slightest sensitivity to an incorrectly chosen parameter can be decisive for the outcome. Therefore, a risk analysis is suitable to obtain a clearer picture of the events that can occur during a fire scenario with a certain probability and associated consequences. See the next section on risk analysis.

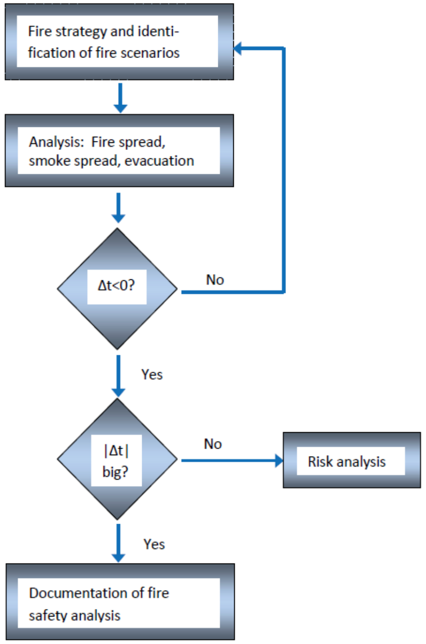

Figure 18.1. Schematic representation of the calculation procedure, including a sensitivity analysis.

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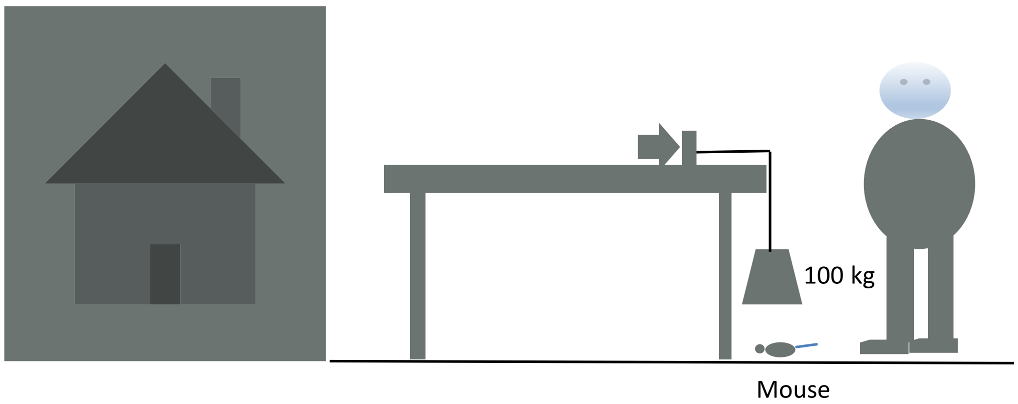
The risk concept

Risk for the mouse?
Risk for the house?
Risk for the man?



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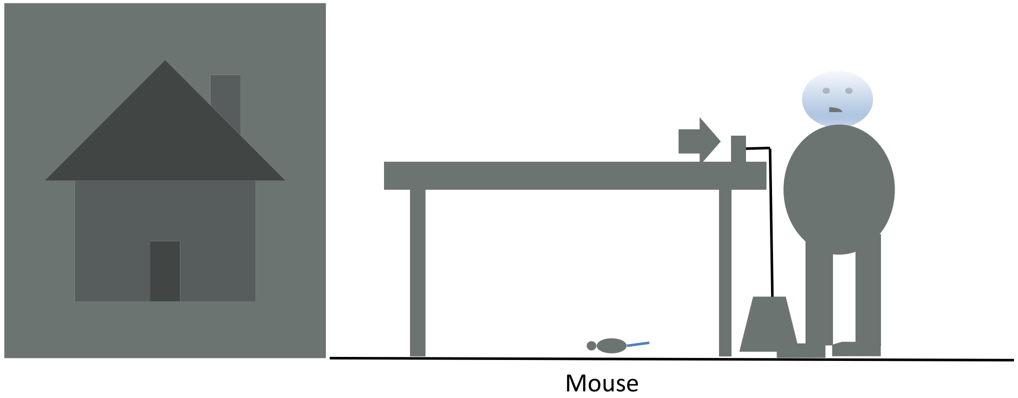
The risk concept

Risk for the mouse?
Risk for the house?
Risk for the man?



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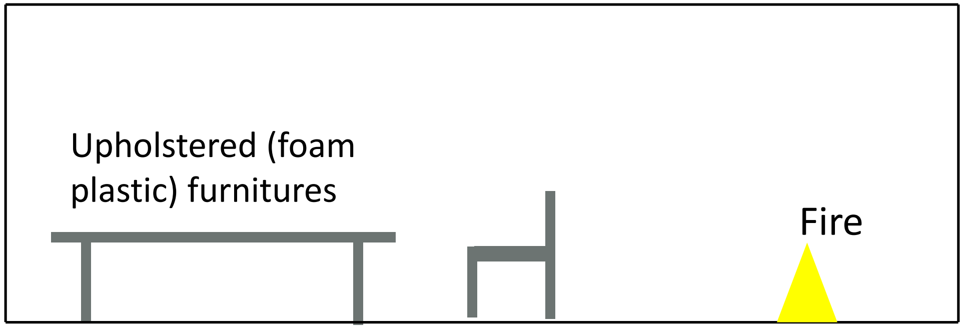
The risk concept

Risk for the inhabitants?

BIG RISK!



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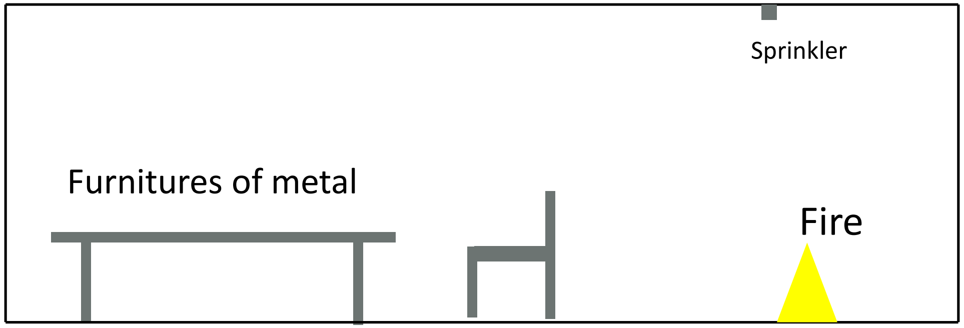
The risk concept

Risk for the inhabitants?

LOW RISK!

(risk reduction)



A risk level can change over time

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Design process including risk analysis

1. Development of a fire strategy
2. Deterministic consequense analysis
3. Sensitivity analysis
4. Risk analysis
5. Risk assessment

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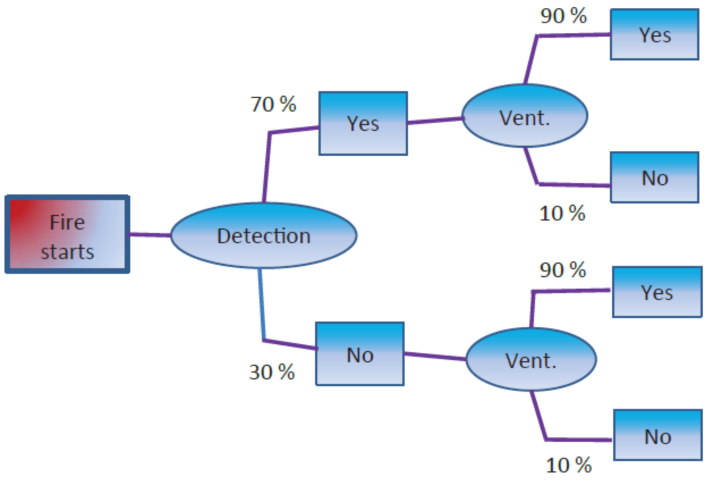
Risk analysis – event tree



Proba-bility	Conse-quense
0.63	0
0.07	4
0.27	2
0.03	6

Figure 18.2. Example of an event tree. An event tree describes the scenarios that may arise as a result of a fire. The probability and impact for each scenario is calculated. The numbers indicated under consequence could be the number of people exposed to critical conditions.

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Risk analysis – input for risk profile

Table 18.1. Input data to the risk profile.

Consequense	Probability	Cumulative	1-cumulative
0	0.63	0.63	0.37
2	0.27	0.90	0.10
4	0.07	0.97	0.03
6	0.03	1.00	0.00

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Risk analysis – Risk profile

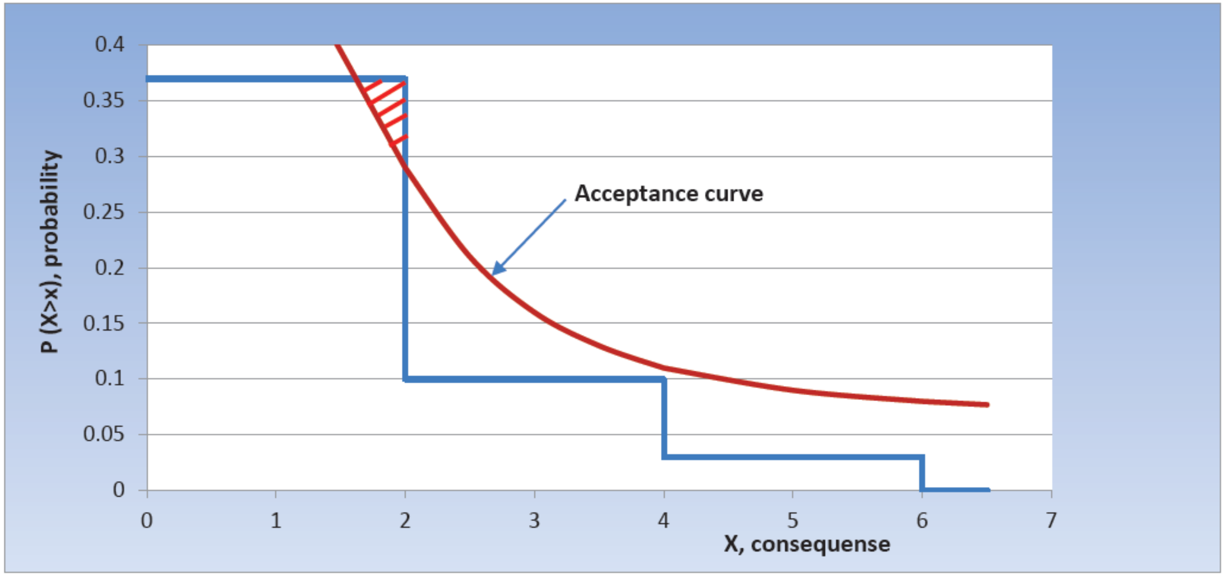

Figure 18.3. Risk profile of the event tree in Figure 18.2.

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Risk analysis

- **Individual risk**: The probability that one or more persons are exposed to critical conditions $P(X>1)$
- **Mean risk:** Medium risk is the fulcrum of the risk profile. Calculated by $\Sigma P \cdot X$ (sum of risk, i.e. probability ·consequence)

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Risk analysis – other tools (risk matrix)

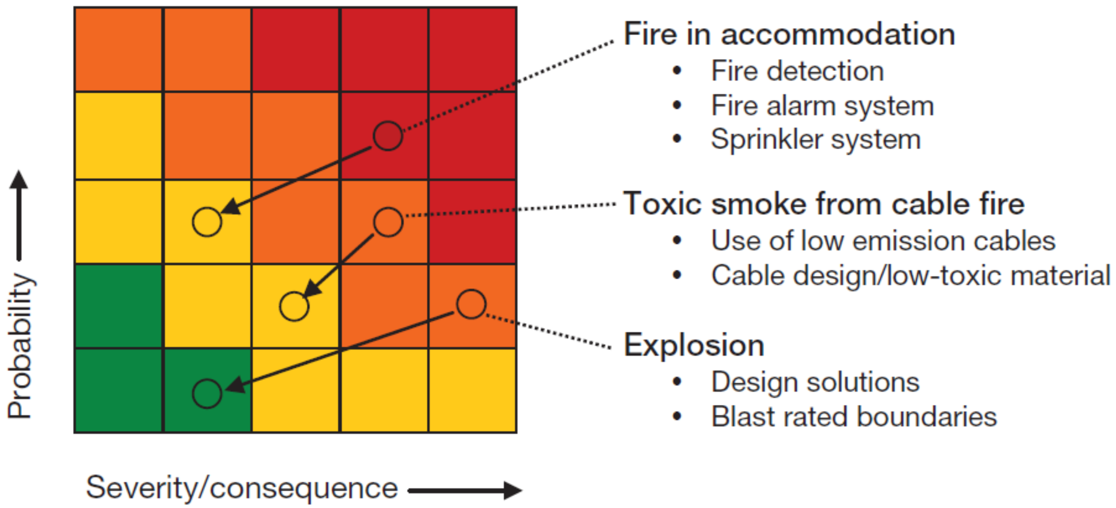

Figure 18.4. Example of a risk matrix for fire hazards to people.

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Documentation

Consist of the following parts:

- Fire strategy
- Fire analysis
- Evacuation analysis
- Comparison
- Operation and maintenance plan
- Reporting

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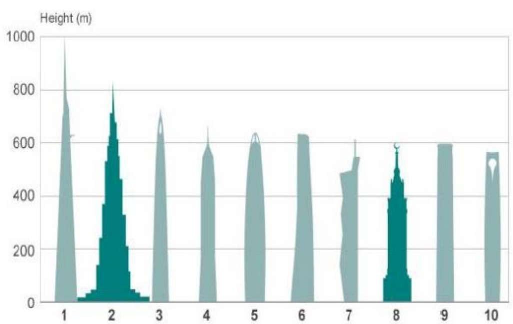
Future challenges (FSE)

- *High-rise fire safety (evacuation etc.)*
- *Carpark fires (structures)*
- *Modern bulding fires (EPS, PIR, PUR, PF)*
- *Standardising (test, classification etc.)*
- *Fire service installations*
- *Energy renovation and fire safety*
- *Energy storage and fire safety*
- *Solar systems*
- *Facades and fire safety*
- *Toxicity*

Phenol Foam

Grenfell (London) juni -17

Downtown Hotel fire (Dubai)



Wiesenhof – chicken slaughterhouse (28. March 2016) Niedersachsen, Germany

Foto: Bodo Wolters / Leer https://idw-online.de/de/image152682

Gigantium (Aalborg) july -17

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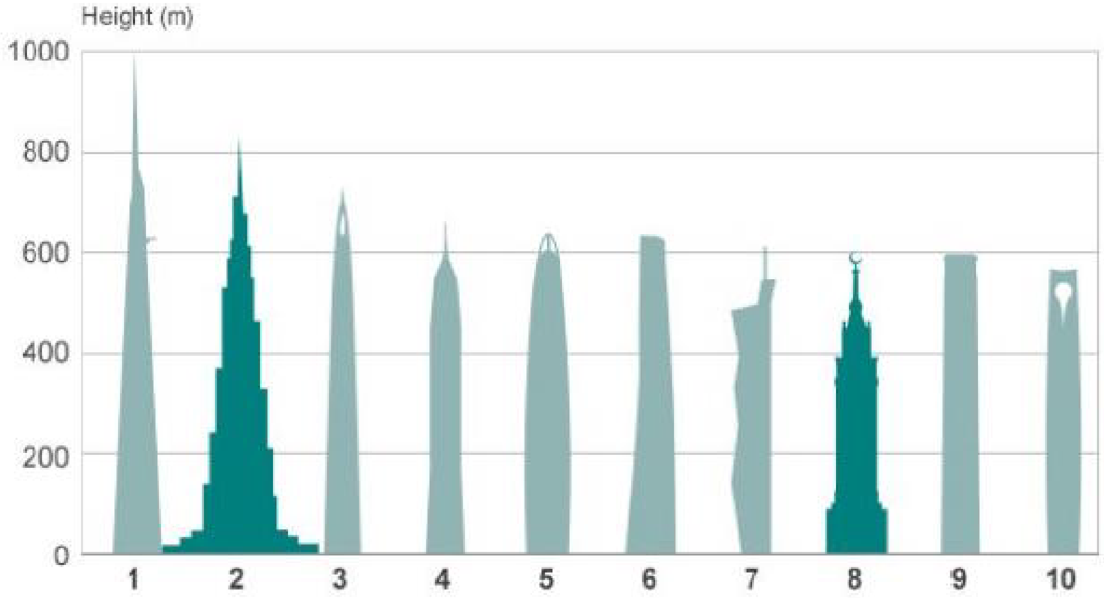
High-rise



1 Kingdom Tower, Saudi Arabia
2 Burj Khalifa, UAE
3 Suzhou Zhongnan Centre, China
4 Ping An Finance Centre, China
5 Wuhan Greenland Centre, China
6 Shangai Tower, China
7 KL118 Tower, Malaysia
8 Makkah Royal Clock Tower Hotel, Saudi Arabia
9 Golden Finance 117, China
10 Baoneng Sheneng Shenyang Global Finance Centre Tower, China

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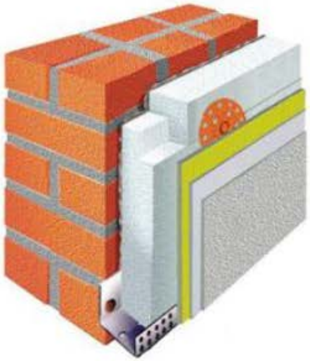
Facades – 2 types

Bulk technology

One of the most commonly used ways of achieving and meeting the conditions of energy saving and building thermal protection is the use of bulk technology:

- *composite systems like external thermal insulation system (ETICS)*
- *metal composite system e.g. aluminium composite panel (ACP).*



Ref. (Dubravka et al 2017)

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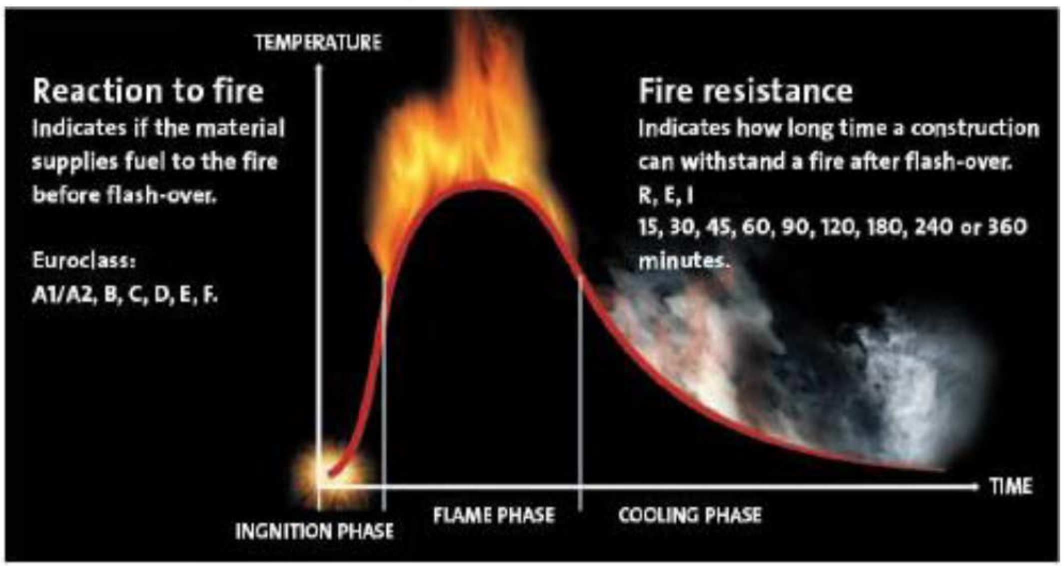
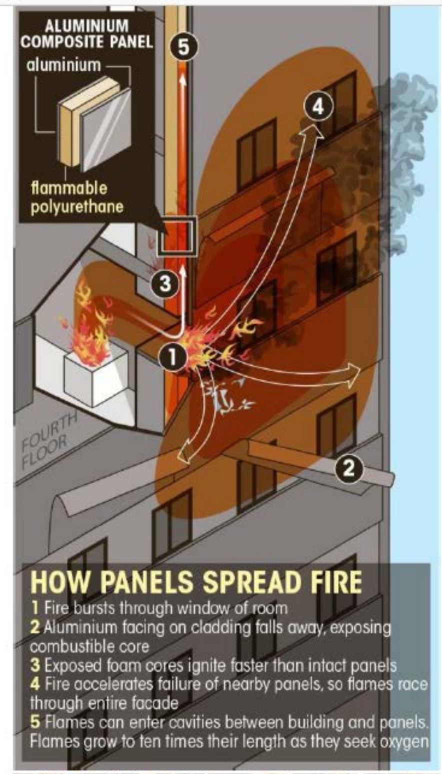
Principle of fire spread on a facade

Fire properties of materials and structures



Ref. (Dubravka et al 2017)



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K-FORCE

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Thank you
for your attention

Associate Professor Lars Schiøtt Sørensen, PhD
Lsso@byg.dtu.dk

Knowledge FOr Resilient soCiEty