IMFSE MSc Thesis

Cost-Benefit Analysis of Fire Spread Scenarios in Large Compartmentalized Warehouses

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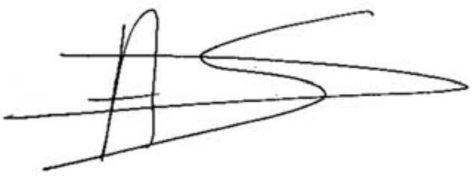

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Abstract

A new model for Cost-Benefit Analysis of the fire safety measures, and particularly compartmentation, in distribution centers was created as a detailed investigation of an existing model revealed several shortcomings.

The new model was constructed in such a way that it computes all possible failure scenarios for a given building layout, which made the necessity to reduce the amount of non-interchangeable events irrelevant. As flashover was identified to be the main failure event, a hands-on methodology was presented to perform a probabilistically risk assessment of its occurrence and consequence. The synergy between the model and the probabilistic risk assessment allowed for an accurate estimate of the damage cost, a vital parameter for the CBA.

A method was engineered to establish the minimum compartment size in function of a medium, fast and ultra-fast fire growth rate, resulting respectively in a floor area of 400 m^2, 1,600 m^2 and 8,100 m^2. Also, a thorough evaluation of the compartment value per unit floor area was made, and the results indicated an interval where compartmentation has a significant benefit compared to the installation of a sprinkler system. It was found that building sizes smaller than 30,000 m^2 require a significant increase of compartment value, while excessive values show a favor for sprinkler installation. In addition, the impact of the compartment barrier material was researched and found to be significant. Therefore, a methodology was developed for the private investor to evaluate the extra investment of a more redundant barrier.

The framework was set-up in such a way that it provides a construct for the non-expert to single-handedly assess the risk he or she is exposed to, which empowers the private investor to actively participate in the debate on rational decision making for safety investments.

The main conclusion is that, compartmentation can only be considered beneficial for building sizes larger than 30,000 m^2, or for compartment values in excess of 2,000 euro/m^2. The application area for the measure is thus limited to very large warehouses or similar industrial buildings.

Een nieuw model voor de uitvoering van een Cost-Benefit-Analysis CBA voor risico beperkende maatregelen, toegespitst op compartimentering in grote industriële opslagplaatsen, was uitgevoerd nadat een gedetailleerd onderzoek van het vorige model verschillende tekortkomingen blootlegde.

Het nieuwe model is zo ontwikkeld dat het alle mogelijke brand verspreidings scenario's voor een gegeven gebouw analyseert. Omdat Flashover geïdentificeerd was als de hoofdoorzaak voor een monetair verlies, was een probabilistisch risicoonderzoek van de parameter noodzakelijk. De synergie tussen het nieuwe model en de probabilistische benadering van flashover laat toe om de residuele schade kost te bepalen, een cruciale parameter voor de CBA.

Een methode werd ontwikkeld om de minimum compartiment grootte te berekenen in functie van de brandgroei snelheid. Voor een medium, snelle en ultrasnelle groei werden respectievelijk een vloeroppervlak van 400 m^2, 1600 m^2 en 8100 m^2 bepaald. Daarnaast toonde een studie aan dat compartimentering een significant voordeel heeft ten opzichte van een sprinkler systeem voor specifieke intervallen van vloeroppervlak waarde. Gebouwen met een vloeroppervlak kleiner dan 30,000 m^2 hebben een exponentiele stijging in waarde nodig om voordelig te zijn. Ook werd aangetoond dat het gebruikte materiaal voor de compartimentering muur een impact heeft op de CBA, hierdoor werd een methode gemaakt om te beoordelen of de meer investering voor een beter materiaal voordelig is of niet.

De opzet van de gebruikte methodologie was een construct te maken dat door experten en niet-experten gebruikt kan worden om eigenhandig de blootstelling aan risico te bepalen, hierdoor kan de privé-investeerder actief deelnemen aan het debat over veiligheidsmaatregelen.

Het hoofdbesluit over compartimentering is dat het hoofdzakelijk voordeling kan zijn voor gebouwen in de grootorde van 30000 m^2 of voor gebouwen met een vloeroppervlak waarde hoger dan 2000 euro/m^2. Het toepassingsgebied van de veiligheidsmaatregel is dus voornamelijk voor zeer grote warenhuizen.

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Nomenclature

The reader is asked to refer to this nomenclature while reading, to avoid introducing all the variables throughout the text.

Acronym

ALARP	As Low As Reasonable Practicable [-]
BRE	Building Research Establishment [-]
CBA	Cost-Benefit-Analysis [-]
CBS	Central Bureau Of Statistics (Netherlands) [-]
FO	FlashOver [-]
HRR	Heat Release Rate [kW]
LQI	Life Quality Index [-]
MHCLG	Ministry of Housing, Communities and Local Government (London) [-]
NPV	Net Present Value [euro]
PBD	Performance Based Design [-]
PRA	probabilistic Risk Assessment [-]
TNO	Netherlands |Organisation for applied Scientific Research [-]

Special characters

$\dot{Q}(t)$	is the Heat Release Rate in function of the time [kW]
$\dot{Q}$	is the Heat Release Rate [kW]
$\dot{Q}_{fo}$	is the HRR needed for FO [kW]
$\dot{Q}_{fuel,max}$	is the peak fuel-controlled HRR when $a_f = A_f$ [kW]

$\dot{Q}_{fuel}$ is the peak fuel-controlled HRR [kW]

$\dot{Q}_v$ is the peak ventilation-controlled HRR [kW]

$\dot{Q}_\alpha$ is the HRR based on the αt^2 fire [kW]

$\dot{m}''$ is the mass loss rate of the fuel, MLR [kg/s/m^2]

$\dot{m}_a''$ is the mass flow of air into the compartment through the openings [kg/s/m^2]

$\dot{q}''$ is the heat flux [kW/m^2]

$\dot{q}_{fo}''$ is the heat flux needed for FO [kW/m^2]

$\dot{q}_{free}''$ is the heat flux induced by a free burning fire [kW/m^2]

$\dot{q}_{fuel}''$ is the heat flux induced by $\dot{Q}_{fuel}$ [kW/m^2]

Upper case leters

A_0 is the area of the vertical openings opening [m]

A_h is the area of horizontal openings in the roof [m^2]

A_T is the total internal surface area in the compartment, excl. ventilation openings [m^2]

$A_{ext,f}$ is the total floor area of the building [m^2]

A_f is the floor area of the compartment [m^2]

A_o is the area of the ventilation openings [m^2]

A_t is the total internal surface area in the compartment, including the ventilation openings [m^2]

A_v is the area of the vertical openings [m^2]

$B(p)$ are the total cost resulting from a failure when there are no, extra, risk mitigation measures installed, i.e. the maximum possible benefits B that can be made when installing a safety system [euro]

$[B(p) - D(p)]$ is the value that is protected due to the mitigation measure and should be greater than $C(p)$ for the system to be feasible, i.e. $Z(p) \geq 0$

$C(p)$ is the implementation cost of the safety measure [euro]

$C_{l,i}$ is the length of comp. i [m]

$C_{w,i}$ is the width of comp. i [m]

$D(p)$ is the cost, direct and indirect, resulting from a failure with a safety measure installed

D_D are all the damage states of a system [-]

E Energy available in an enclosure [kJ]

$E[C]$ Expected Consequences [-]

EX exposure

$F(A)$ is the frequency of a potentially serious fire in the enclosure [yr^{-1}]

$F_Y(y)$ is the cumulative distribution function of Y for the value y [-]

F_X is the cumulative distribution function of X [-]

F_{ext} is the frequency of an ignition in the building [yr^{-1}]

F_i is the frequency of an ignition in comp. i [yr^{-1}]

$F_{norm}(A)$ is the accepted frequency that the fire area will be bigger than the compartment area [yr^{-1}]

$F_{os}(A) = F(A)P_1P_2P_3P_4$ is the expected frequency that the fire area will be bigger than the compartment area [yr^{-1}]

G limit state function to describe the failure of a fire barrier [-]

H is the height of the compartment [m]

H_o is the height of the vertical ventilation openings [m]

L is the useful life of the mitigation measure under review [yr]

N Number of compartments [-]

O is the opening factor [$m^{1/2}$]

$P(EX)$ is the probability that the exposure happened [-]

$P_{1,0}$ is the probability that takes into account the possibility of suppression by occupants or the fire service when the fire is still minimal. $P_{1.0} = 0.04$ is recommended

$P_{1,1}$ is a probability that takes into account extra measures, e.g., the removal of heat sources, use of non-flammable products instead of flammables, separation of ignition sources and flammable materials

PV is the value of future cost and benefits at the time of construction [euro]

P_{act} is the failure probability of the active measures [-]

$P_{f,0}$ is the annual failure probability without the mitigation measure [yr^{-1}]

$P_{f,p}$ is the annual failure probability with the mitigation measure [yr^{-1}]

P_f the annual failure probability [yr^{-1}]

$P_{fo,after,i}$ is the annual FO probability due to ignition in comp. i upon arrival of the fire service after FO [yr^{-1}]

$P_{fo,before,i}$ is the annual FO probability due to ignition in comp. i upon arrival of the fire service before FO [yr^{-1}]

$P_{fo,ext}$ is the annual failure probability due to ignition in the building [yr^{-1}]

$P_{fo,i,j}$ is the annual FO probability in comp. j due to a fire spread scenario from comp. i to comp. j [yr^{-1}]

P_{fo} is the probability that a local fire grows to a compartment fire [-]

$P_{fuel,ext}$ is the probability that a local fire will develop into FO in the building [-]

$P_{fuel,i}$ is the probability that $\dot{Q}_{fuel} \geq \dot{Q}_{fo}$ in comp. i [-]

$P_{fuel,j}$ is the probability that $\dot{Q}_{fuel} \geq \dot{Q}_{fo}$ in comp. j [-]

$P_{fuel,k}$ is the probability that $\dot{Q}_{fuel} \geq \dot{Q}_{fo}$ in comp. k [-]

P_{fuel} is the probability that $\frac{\dot{Q}_{fuel}}{A_f} \geq \frac{\dot{Q}_{fo}}{A_f}$ given that $t_E > t_{ch}$ or $\dot{Q}_v > \dot{Q}_{fo}$ [-]

$P_{fw,i\rightarrow j}$ is the failure probability of the fire wall between comp. i and j [-]

$P_{fw,i\rightarrow j;con}$ is the failure probability of compartmentalization wall between comp. i and j, determined by the material used to make the separation

$P_{fw,i\rightarrow j;pen}$ is the combined failure probability of all relevant penetrations in the compartmentalization wall between comp. i and j, determined by the level of detail administered in making the connection between the wall and intersecting elements

$P_{fw,j\rightarrow k}$ is the failure probability of the fire wall between comp. j and k [-]

P_{fw} is the failure probability of the fire wall [-]

$P_{lf,ext}$ is the probability of an ignition to grow to a local fire in the building [-]

$P_{lf,i}$ is the probability of an ignition to grow to a local fire in comp. i [-]

P_{lf} is the probability of an ignition to grow to a local fire [-]

$P_{pass,j}$ is the failure probability of the extra passive safety measures in comp. j [-]

$P_{pass,k}$ is the failure probability of the extra passive safety measures in comp. k [-]

$P_{poss,fo,ext}$ is the parameter that defines if FO is possible or not for the building [-]

$P_{poss,fo}$ is the parameter that defines if FO is possible or not [-]

P_{spr} is the failure probability of the sprinkler system [-]

$P_{suppr,after}$ is the failure probability of the fire service upon arrival *after* FO [-]

$P_{suppr,before}$ is the failure probability of the fire service upon arrival *before* FO [-]

R_T thermal resistance of the element

S_T thermal exposure of fire

S_{ext} are the total consequences for the whole building [euro/fire]]

S_i are the total consequences for comp. i [euro/fire]

V is the volume of compartment [m^3]

$X \sim N(250,50)$ is a normally distributed variable to represent the distribution of $\dot{q}''_{fuel}$.

X_c is the combustion efficiency, accounting for incomplete combustion, $X_c \leq 1$ [-]

$Y \sim N(200,40)$ is a normally distributed variable to model the failure probability of the fire service with mean 200 and standard deviation 40

Z is the total (net) utility (benefit)

Lower case letters

h_{eq} is the weighted average of window heights on all wals [m]

h_k is the effective heat transfer coefficient [kW/m^{2}K], see [1, pp. 121-123]

a is the disproportionality threshold

a_{contr} is the fire area that gives the fire service a failure probability of 0.5 [m^2]

a_f is the fire area at t_{int} based upon the αt^2 fire [m^2]

$c(d)$	are the consequences of a given damage state
$c(t)$	is the loss rate or continuous cost rate [euro/yr]
c_{t_i}	are the discrete future costs [euro]
c	is the constant cost rate [euro/yr]
c_0	is the constant cost rate without mitigation measure [euro/yr]
c_0	is the installation cost at $t = 0$ [euro]
c_{inst}	is the implementation cost [euro]
c_p	is the constant cost rate with mitigation measure [euro/yr]
d	is a damage state [-]
$f_D(d\|EX)$	is the probability distribution function of the damage state, given that the exposure happened [-]
$f_{RS}(r_T, s_T)$	is the joint PDF
$f_c(c)$	the probability density function, PDF, that describes the distribution of the consequences c
$g(r_T s_T)$	is the failure domain
k_1	is the coefficient that relates the F(A) and the floor area for industrial buildings [$m^{-1}yr^{-1}$]
k_2	is the coefficient that relates the F(A) and the floor area for other non-residential buildings [$m^{-2}yr^{-1}$]
k_b	is the conversion factor [$min.m^2/MJ$], see Table 38
k_c	is the correction factor function of the material's structural cross-sections [-], see Table 39

m	is the combustion factor (for most cellulosic materials $m = 0.8$)
m_t	is the annual maintenance cost [euro/year]
n	is the amount of different costs [-]
n_0	represents the compartments where ignition can happen [-]
$q_{f,d}$	is the design fire load density [MJ/m^2], see Eq. (84)
$q_{f,k}$	is the characteristic fire load density per unit floor area [MJ/m^2], see Table 35
r	is the annual discount rate [yr^{-1}]
$s_{c,i}$	are the direct and indirect consequences per unit floor of comp. i [euro/m^2/fire]
s_{event}	are the direct and indirect consequences associated with a total loss [euro/fire]
$s_{whole,i}$	are the direct and indirect consequences associated with comp. i [euro/fire]
$s_{c,min,comp}$	is the minimum compartment value needed to return a positive CBA for compartmentation [euro/m^2]
$s_{c,min,spr}$	is the minimum compartment value needed to return a positive CBA for sprinkler installation [euro/m^2]
$s_{c,min}$	is the minimum compartment value needed for sprinkler installation to return a greater Z(p) than compartmentation [euro/m^2]
t_E	is the time needed to release the energy content of the room [s]
t_{ch}	is the characteristic minimum time before all energy in consumed to make FO possible when $\dot{Q}_v < \dot{Q}_{FO}$ [s]
$t_{e,d}$	is the equivalent fire duration [min]
t_{fo}	is the time to FO [min]
t_i	are the discrete points in time at which c_{t_i} occur [yr]

t_{int} is the intervention time of the fire service [min]

t_u is the useful life of the mitigation measure [yr]

w_f is the ventilation factor [-], see Eq. (85) and Eq. (86)

Greek letters

x_0 object specific risk indicator

υ insured value of the building [euro]

δ_n is a factor taking into account the different firefighting measures i, see

Table 37

δ_{q1} is a factor taking into account the fire activation risk due to the size of the compartment, see Table 19

δ_{q2} is a factor taking into account the fire activation risk due to the type of occupancy, see Table 36

μ_F the cost of human losses [euro/fire]

$\mu_{H,0}$ is the cost due to a single failure without the mitigation measure installed [eurp/yr]

$\mu_{H,p}$ is the cost due to a single failure with the mitigation measure installed [euro/fire]

μ_M the cost of material losses [euro/fire]

ρ_{air} is the density of the air, recommended as $\rho_{air} = 1.2$ [kg/m^3]

Δh_c is the heat of combustion [J/kg$_{fuel}$]

ΔC is the net investment cost of the investigated safety feature

ΔRI is the associated change in the risk indicator (< 0)

ΔT is the temperature increase [°C]

γ is the continuous discount rate [yr^{-1}]

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Chapter 1

Introduction

In the retail industry, a trend to move towards regional distribution centers or even a single national center is witnessed [1]. The increase is allocated to the surge in internet shopping. To meet the business requirements, the floor area needs to be in the range of 25,000 to 40,000 m^2, and even 80,000m^2 is possible. To counteract the correlated increase in fire risk the MHCLG, Ministry of Housing, Communities and Local Government in London, has proposed a societal plan to limit the maximum, unsprinklered, compartment size of warehouses to 440,000 m^3. Research conducted by BRE [1] interpreted this as a floor area of 40,000 m^2, assuming a building height of 11.5 – 12 m, which is the maximum height a turret truck can reach.

Today about 20 – 50 % of the warehouses are voluntarily sprinklered to protect material property and business continuity [1]. This is in contrast with the UK Warehouse Association, stating that sprinklers generally cannot be justified in a cost-benefit assessment [1]. The advice is given to reduce fire risk by addressing escape routes, fire loads, management and security rather than restricting compartment size. Considering an ignition rate on a yearly basis [2, 3, 4] these measures do not prohibit the possibility of a potentially severe fire. They can reduce it, but there will always be a chance that a fire grows beyond a controllable size. Without active or passive mitigation measures installed the private owner then has a *risk* of experiencing a total loss [2].

Looking at a national distribution centre, it is very likely that all of a business stock might be gathered in one place. A private investor with a risk-prone approach, i.e., only fulfilling the stated societal provision, could face a *direct loss* of approximately £8,400,000[1]. Hence, it makes sense to protect a business's assets as a total loss would almost certainly mean bankruptcy. An entrepreneur can avoid a scenario like this by investing in safety beyond the societal requirements (e.g., sprinklers, compartmentalization, smoke detection, fire extinguishers).

[1] 40,000 m^2 at a value of £210 per unit floor area.

To make such investments debatable among experts, lay people and investors the expected benefits and consequences must be monetarized and quantized. Doing this in a systematic approach is especially crucial for safety features. Their possible benefits are assessed over a long time span, and relevant concepts are not easy to clarify pragmatically. A *Cost-Benefit Analysis* CBA is a tool designed for precisely this purpose: systematically assess the merits and weaknesses of any investment.

The scope of this thesis is to provide a tool for conducting a private Cost-Benefit Analysis CBA for compartmentation. The measure is generally only used to define an upper-boundary for a non-sprinklered area, and the possibilities as a useful risk reduction tool are neglected. Also, available studies focus only on sprinklers or, like NEN6079 [2], are conducted from a societal point of view. The primary focus being fire spread to neighboring plots and thus wholly neglecting internal fire spread. The governing reason for the deficiency is that code restrictions apply to safety of occupants to make sure that there is sufficient safe egress time rather than protection of private interests.

The problem for compartmentalization lies within projecting the damage cost, i.e., the residual cost resulting from a fire event with compartmentation installed. The governing reason is the dependency on the fire spread path. Steps towards a viable mathematical model to identify all scenarios have been undertaken in the past. The methodology of the previous example provided an invaluable basis for this thesis and is analyzed in Section 1.6. Nevertheless, because of the many restrictions inherent to its thought process, it is not deemed accurate enough for this thesis. A big part of the research was dedicated to constructing a new model, presented in Section Chapter 3.

1.1. A definition for Risk

De Sanctis [3] defines risk R as the expected consequences $E[C]$ considering all damage states D_D of a system, i.e., a failure of the system or exceedance of a pre-set boundary. For a damage state d the related consequences $c(d)$ are multiplied with the probability density function $f_D(d|EX)$ of the damage state given the probability that the exposure EX happened $P(EX)$ [3]:

To avoid introducing all the variables and abbreviations used in this thesis the reader is referred to the previously provided nomenclature.

$$R = E[C] = \int_{D_D} c(d) * f_D(d|EX) * P(EX) dD \quad (1)$$

The consequences can include loss of live, injuries, economic losses, business interruption, cultural losses, etc. To be able to make rational decisions it is convenient to express them in terms of monetary losses.

Equation (1) can be simplified by selecting incident scenarios and assigning a probability and consequence to each. These scenarios are usually represented by an event tree [3]. Eq. (1) can then be expressed as $risk = uncertainty\ x\ consequences$.

1.2. The societal investor versus the private investor

1.2.1. Tolerability and residual risk in the societal ALARP criterion

The goal of societal safety measures is to make sure a design is tolerable and that the remaining risk is ALARP, as low as reasonably practicable [4] [3]. Whether a design is tolerable or intolerable is determined by the possible consequences C and the probability, or frequency F, of an event [5]. These two parameters are represented by a risk curve in the FC-diagram, see Figure 1. When the risk curve is in the dark grey area the design itself must be reviewed. Curves in the grey and white area are tolerable, and thus the societal ALARP requirement applies to reduce the residual risk further. The difference is that for the “de minimis” region no active research has to be conducted to find extra cost-effective safety measures.

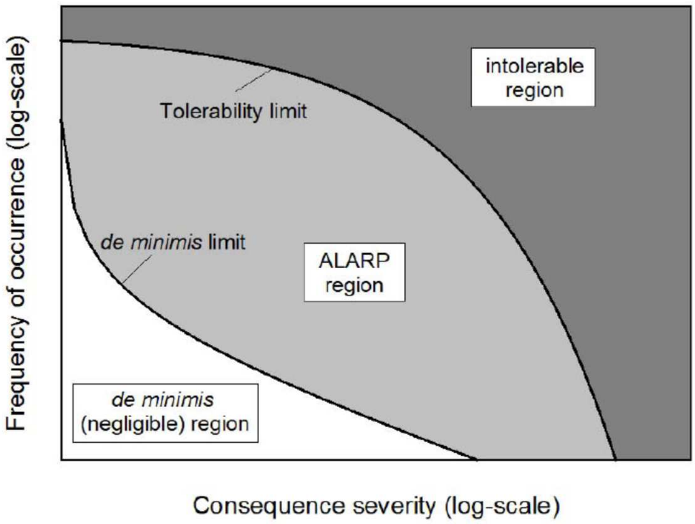

Figure 1: Generalized frequency-consequence diagram [5]

To fulfil the societal ALARP criterion regulatory agencies or authorities should aim for the maximal possible risk reduction that society is willing to pay for, SWTP [3]. In other words, how much resources a community wants to allocate to save one person[2]. Hence, the proposal under review should be implemented up to a point where there is a gross disproportion a between the chance in risk ΔRI and the cost to reduce it ΔC [6], once past this point more life’s can be saved elsewhere [7]:

$$\frac{\Delta C}{-\Delta RI} \leq a \tag{2}$$

[2] The Life Quality Index, LQI, was introduced by Nathwani et al. (1997) to allow for rational decision making on safety investments. Based upon the expected length of life, in good health and wealth, it avoids the ethical dilemma to assign a monetary value to life [3]. When authorities don’t respect the ALARP boundary a net loss of societal welfare occurs as more lives can be saved through other, more targeted, risk reduction measures.

1.2.2. From societal ALARP criterion to the private CBA

Parameter a in Eq. (3) is the proportional constant translating the change in risk into an equivalent monetary value [5]. This is in contrast with Eq. (2) where a is the disproportionality constant. In the latter, it specifies the gross disproportion needed between cost and risk before a safety measure is considered as not cost effective. The change from Eq. (2) to Eq. (3) can be explained by considering the gross disproportion reference as a part of societal risk aversion which is already included in the tolerability assessment. Eq. (3) can be interpreted as a pure societal cost-benefit analysis.

$$\Delta C \leq a(-\Delta RI) \tag{3}$$

It is evident that a clear distinction must be made between societal and private investors. The goals are respectively to enlarge societal utility and personal utility. The societal ALARP criterion provides a *minimum requirement* for any private cost-benefit consideration [8],[9]. Once this is fulfilled, the private decision-maker is free to invest in safety design beyond. On the other hand, he or she can also adhere to a risk-prone attitude [5]. In other words, as long as no possibility of ruin exists, i.e., the probability of unbearable consequences, the entrepreneur can gamble on not having an incident.

The methodology and definitions behind the societal ALARP criterion can be modified to fit a business owner's perspectives. Whereas the societal approach is based on the SWTP with a goal to save lives, the private CBA is based upon the entrepreneur's willingness to pay in order to safeguard work continuity, material protection, legacy protection, saving lives, etc.

1.3. The CBA and the total net utility or present value

The general formulation of a CBA, accepted for both the societal and private investor, is given by Eq. (4) [5]. In essence, it represents the same concept as Eq. (3). The maximum possible benefits $B(p)$ reduced with the damage cost $D(p)$ signifies the reduction in expected fire-induced damages. The optimization is realised by changing one or more design parameters p (e.g., a change in the size of compartments, number of compartments, firewall material). The shift in risk must be in balance with the associated costs $C(p)$ for an investment to be beneficial. In other words, the net total utility $Z(p)$ must be greater than zero.

$$Z(p) = B(p) - C(p) - D(p) - \cdots \tag{4}$$

The occurrence of an event in a building without any safety measures will lead to the maximum possible risk a fire can induce. It can be intuitively understood that the risk of this reference scenario is equal to the maximum possible benefit an investment can produce. After all, a safety measure cannot reduce the risk below zero and thus it potential profits cannot be higher than the maximum possible risk. As risk reduction tools are never impeccable the occurrence of an incident will still introduce a specific cost, i.e., the damage cost. It is trivial that its magnitude is assessed on a scenario with safety measures installed. Eq. (4) is thus a tool that compares the reference state without mitigation measure to a state with mitigation measure.

1.3.1. Time effects

Costs and benefits happen at different, and possibly random, points in time and thus Eq. (4) must account for time effects. Money that is earned, or spend, in the future doesn't have the same value today. Time effects are extraneous to inflation, and the following explanation is thus inherent to the assumption that the same amount of goods can be bought with a euro now and in the future. There are two reasons for the depreciation. If a person can choose to get a hundred euro today or a hundred euro over ten years, then the first option is the most valuable as that hundred euro can be invested over ten years to gain more profits, i.e., earn interest on a bank account. Secondly, what will happen in the future is uncertain, and thus money spend, or earned, in the future has a particular risk that money spent, or received, today doesn't have. Accounting for time effects will thus efficiently reduce costs made and benefits earned in the future. Reducing costs and benefits to their present value PV is called discounting and is done by dividing the costs c_{t_i} that happen at a certain time t_i in the future with the annual interest rate r. Once this is done the summation of all discounted costs is taken to get the total PV [8]:

$$PV = \sum_{i=1}^{n} \frac{c_{t_i}}{(1+r)^{t_i}} \tag{5}$$

The valuation of the costs in Eq. (5) happens at discrete intervals, e.g., daily, monthly, quarterly, semi-annually or annually. For a more precise calculation Eq. (6) uses a continuous discounting rate γ [8]. This is especially important for high-risk investments or events.

$$PV = \sum_{i=1}^{n} c_{t_i} \exp(-\gamma t_i) \tag{6}$$

Equating Eq. (5) and (6) gives Eq. (7) which converts an annual interest rate r into a continuous discount rate γ [10].

$$(1+r)^{t_i} = \exp(\gamma t_i) \Leftrightarrow (1+\mathrm{r}) = \exp(\gamma) \Leftrightarrow \gamma = \ln(1+r) \\ \Leftrightarrow r = \exp(\gamma) - 1 \tag{7}$$

The difference between the discrete and continuous discounting is shown, for a single cost of one euro, in Figure 2. From the chart can also be derived that a low discount rate favours gains in the future and vice versa. For example, when a vertical line is drawn at $t = 40$ years, it intersects the $\gamma = 0.1$ line in a $PV \approx 0.01$. Meaning that an investment today is only favourable if it costs less than 1 percent of the future gain. Doing the same for the $\gamma = 0.049$ line results in a PV of approximately 0.2 and thus the investment today can be up to 20 percent of the future gain before it is disadvantageous. As mitigation measures usually save lives over many years, the societal discount rate should be small to make investments in mitigation measures today profitable. A societal discount rate equal to the long-term economic growth is recommended for societal investment [8]. Private investors can choose an arbitrary γ if the minimum boundary condition of ALARP is fulfilled.

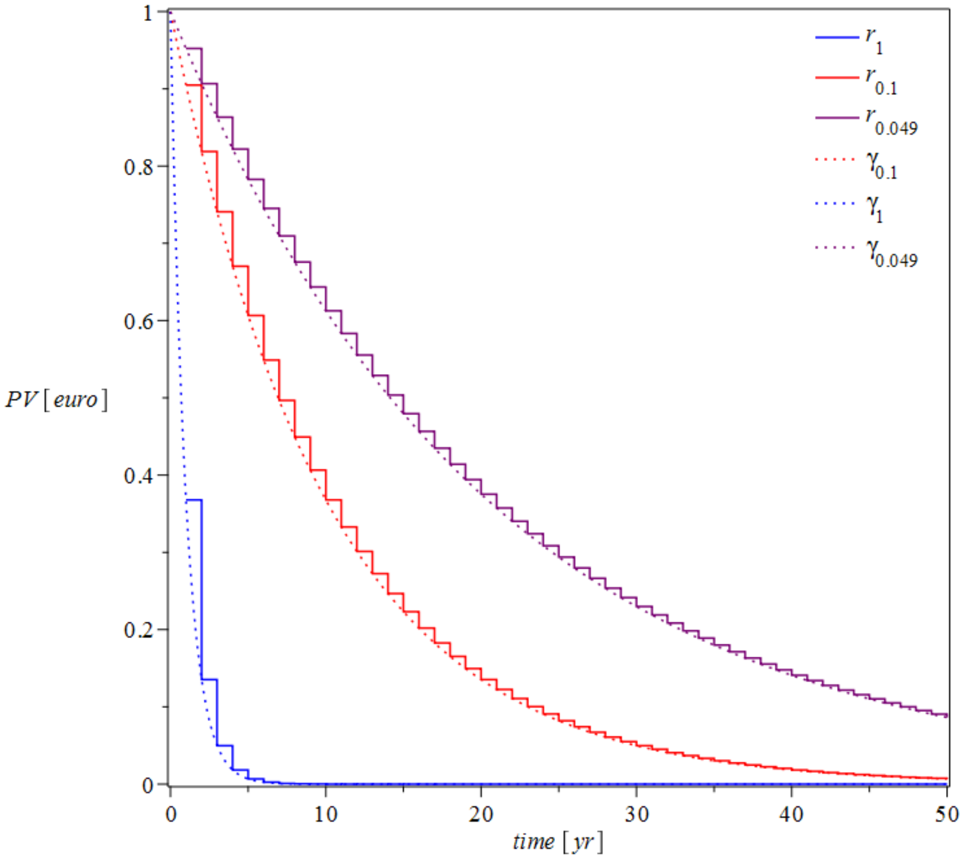

Figure 2: The difference between continuous γ and discrete discounting r and the effect of various discount rates on the present value PV

When fire losses are multiplied by the occurrence rate of a fire the loss rate or continuous cost rate $c(t)$ is obtained. Assuming a constant cost rate c, and that the time of rebuilding is small compared to the time between events leads to the following formulation for the PV of the total costs over the useful life t_u [8]:

$$PV = \frac{c}{\gamma} * (1 - \exp(-\gamma t_u)) \tag{8}$$

The constant cost rate c in Eq. (8) is interpreted as the expected cost due to a single failure with or without the mitigation measure installed. The total PV is thus the result of a renewal process where after an event there is an immediate reconstruction [11]. Furthermore, as the time goes to infinity the value of a dollar goes to zero, see Figure 2, and thus the PV cost, and benefit, line reach a horizontal asymptote. The effect of an infinite time horizon is mathematically represented by Eq. (9).

$$PV = \frac{c}{\gamma} \tag{9}$$

$t_u \rightarrow \infty$ would be the case for societal investments, as a societies need for a construction is not related to the conceptual, private, design life [8]

1.3.2. The expected present value of the consequences and implementation cost

Combining Eq. (8) and the definition of risk, see Eq. (1), results in the expected PV of the damage cost $D(p)$ and the expected PV of the possible benefits $B(p)$ [5]:

$$D(p) = c_p \frac{P_{f,p}}{\gamma}[1 - \exp(-\gamma t_u)] \tag{10}$$

$$B(p) = \ c_0 \frac{P_{f,0}}{\gamma}[1 - \exp(-\gamma t_u)] \tag{11}$$

There is no need to discount the implementation cost c_{inst} since the investment is made at $t = 0$. When there is an annual maintenance cost m_{t_i} accompanying a safety measure, $C(p)$ is the sum of the original investment and the PV of total maintenance cost. With a continuous discounting rate γ and a constant cost rate C(p) is represented by:

$$C(p) = c_{inst} + \frac{m}{\gamma} * (1 - \exp(-\gamma t_u)) \tag{12}$$

1.3.3. Optimizing the investment in the safety feature

The ideal correlation between costs and benefits can be found by taking the derivative of $Z(p)$. Considering one optimization parameter and maximising the useful life t_u the mathematical representation is given by Eq. (14) [5].

$$\frac{dZ(p)}{dp} = \frac{d}{dp}\left[c_0 \frac{P_{f,0}}{\gamma} - C(p) - c_p \frac{P_{f,p}}{\gamma}\right] \tag{13}$$

Because the reference situation, subscript 0, is independent of the optimization parameter it reduces to zero in Eq. (13). Nevertheless, it forms an important quantity to verify if the found value for p results in a positive CBA.

1.3.4. Other tools for the private investor to decide whether an investment is worth undertaking

The time needed to recover the cost from an investment, the payback time, ignores much of the time pattern of receipts and thus it can only be used as a crude rule of thumb [12] and is not relevant for this thesis.

The Internal Rate of Return IRR of an investment is the discount rate, for which the net utility $Z(p)$ is equal to zero [12]. It is the solution for i in Eq. (14), where t_u is the useful life of the investment. An IRR exceeding the market rate of interest indicates that the investment should be undertaken.

$$C(0, L) = \sum_{t=0}^{t_u} Z(p)(1+i)^{-t} = 0 \tag{14}$$

In the calculation of the IRR it is implicitly assumed that intermediate receipts can be compounded at the IRR. This gives a distorted picture as the only appropriate rate for reinvestment is the market rate of interest. Furthermore, if the cash flow at the end of a project becomes negative (e.g., making a plant safe after its useful life) multiple IRR can render Eq. (14) to zero.

With a perfect capital market, lending and borrowing rates are identical, the only universal correct criterion is the Net Present Value NPV or total net utility Z(p), see also Eq. (4). The total net utility is the most relevant parameter in determining if a project is beneficial [12] and is used in this thesis for that reason.

1.4. Performance-based design and a probabilistic risk assessment

When a traditional prescriptive based design is followed the ALARP criterion is implicitly assumed to be fulfilled based on the collective experience of the profession. Meaning that a common and longstanding application in the design exists [5]. However, new problems and ideas arise every day. These lack previous failure events wherefrom the collective experience can learn and thus prescriptive guidance is stretched to its maximum potential [13]. As a result, a trend towards deregulation or performance-based design, PBD, is witnessed [13]. Standard applications of PBD test the design for a few fire scenarios and a pre-defined set of performance criteria. ALARP is still implicitly assumed, based upon the collective experience. Since there is no randomness involved, the methodology is called a *deterministic PBD* [14]. For common problems, the deterministic PBD is a welcome addition. It allows for minor deviations from the code. For challenging projects, e.g., exceptional structures, (very) low probability events or innovative building designs or materials the collective experience of the profession is lacking[15] [5]. For these cases, a PBD in conjunction with a probabilistic risk assessment, PRA, must be conducted. This way the uncertainties can be taken into account, and the ALARP criterion can be explicitly evaluated.

A typical fire event is considered to have five essential stages. Ignition, followed by a growth phase, allowing for intervention, flashover, and lastly decay. Associated with every phase and action are probabilities of failure and success. A standard definition for flashover is the transition of a localized fire to a simultaneous ignition of all combustible materials leading to a general conflagration [16], see Section 1.6. Hence, it makes sense to weigh flashover as a total loss of the compartment. Determining and quantifying the relevant parameters that influence its probability are thus crucial for a viable CBA. The probabilistic approach for flashover followed in this thesis will allow to conduct a PRA for compartmentation

1.5. The total cost of a fire is a multiple of the direct costs

Fire safety measures beyond the societal requirement are too often categorized as not cost beneficial. The problem is that only the direct costs are considered. Various sources [5, 6] debate that moral and ethical aspects should be taken into account when calculating the total cost of a fire (e.g., environmental damage, traffic disruption, emotional damage, loss of production capacity, cost of fire service intervention, cost of legal advice, fines). By doing this, the possible benefits of a risk reduction measure are increased, and the CBA is tilted in favour of implementation.

The problem exists in attributing the right value to each of these cost components. A CBA can be influenced in such a way that the validity of the outcome is useless. In this thesis, rather than assigning values, the magnitude of the needed indirect costs to make a CBA favourable are assessed.

1.6. Analysis of the previous model

As stated before, the last attempt to predict the possible fire spread paths and their probabilities of occurrence provided a basis for this thesis and thus the example is repeated here.

The model [17] provides a calculation method to assess if compartmentation of low rises, for the configurations shown in Figure 3, is beneficial. The first layout has no compartmentalization, i.e., one compartment, and is referred to as the "reference state." In arrangement two and three there are respectively two and four compartments. Per model, the compartments are equal in size and the dimensions are determined by the width B, the length L and the height H of the building.

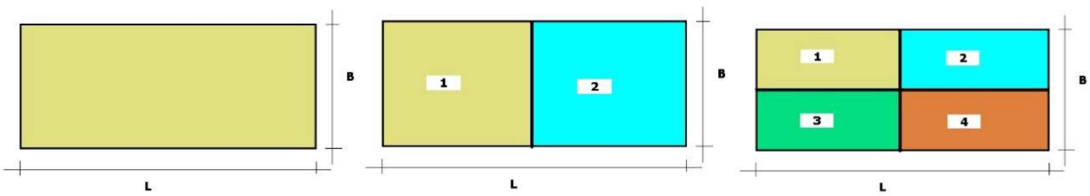

Figure 3: Building layouts on which the previous model is applied: one, two and four compartments [17]

In the derivations below rates are denoted as $P_{x`,x``,x```}$ where x’ describes the model under review, x’’ refers to the parameter under review and x’’’ indicates the compartment for which the derivations are made.

1.6.1. No compartmentalization, the reference state

Since there is only one compartment the floor area A_f is equal to the total building size. Multiplying this by the frequency of a fire occurring per unit floor area per year P_f gives the total fire rate for that compartment:

$$P_{1,F,1} = P_f BL \tag{15}$$

In Eq. (15) P_f is considered to be constant. In reality, the occupation will vary throughout the building and thus also P_f. For example, computers and coffee machines in the office space will present different probabilities for starting a fire than heavy machinery located in the workplace.

Two conditions must be met for FO to occur in compartment one. The first being that a fire must be present $P_{1,F,1}$ and secondly this fire must have a chance to grow to a compartment fire, the probability of flashover P_{fo}. As both conditions must be fulfilled the two terms are multiplied with each other to derive the rate of FO for compartment 1:

$$P_{1,FO,1} = P_{fo} * P_f BL \tag{16}$$

The rate of FO is dependent on the size of the compartment, the total fuel load and the amount of oxygen available in the compartment [18]. Introducing compartmentalization in a building will have a direct effect on these parameters, and thus P_{fo} will vary for each model. For simplicity, the previous example considers the probability of FO as a constant.

The damage per compartment in case of flashover $S_{1,FO}$ is derived by multiplying the compartment floor area with its value per unit floor area S and is given by Eq. (17). S is considered to be a constant but in reality it will vary due to the different occupations that exist in one building; Furthermore, the assumption is made that when FO happens the whole compartment is lost.

$$S_{1,FO} = SBL \tag{17}$$

As this cost will happen in the future a discount rate, as specified in section 0, should be implemented to scale these values to their present value PV.

Multiplying the rate of flashover in compartment one with its consequence gives the total annual loss rate, assuming immediate reconstruction:

$$R_1 = P_{1,FO,1}S_{1,FO} = P_{fo}P_fSB^2L^2 \tag{18}$$

1.6.2. Two compartments

As fire can start in compartment one or two, there will be two different scenarios for this layout. Due to the assumptions made the scenarios are identical, and thus the total loss rate can be derived by multiplying the loss rate for one scenario with the total amount of scenarios, i.e., adding the risk contributions, The starting point for the derivations below is that of a fire starting in compartment one.

Since one compartment is half the building size Eq. (15) is multiplied with 0.5 to get the rate of a fire occurring in compartment one. The result is shown in Eq. (19).

$$P_{2,F,1} = 0.5 * P_f * B * L \tag{19}$$

The rate of FO happening in compartment one is given by Eq. (20).

$$P_{2,FO,1} = P_{fo} * (0.5 * P_f * B * L) \tag{20}$$

The damage in case of FO in compartment one is given by Eq. (21). In reality, there is the possibility that firewater, smoke and heat will cause damage to compartment two. The latter is not considered in this model, and thus the assumption is made that there is no extensive damage in the adjacent compartment if the fire wall doesn't fail.

$$S_{2,FO} = 0.5 * S * B * L \tag{21}$$

Three events must happen for FO in compartment one to cause FO in compartment two. There must be FO in the first compartment, the fire wall must fail to allow fire spread to compartment two, and this secondary fire must grow to a compartment fire. By multiplying the failure rate of the barrier per unit area P_{fw} with its total surface area the overall failure rate of the wall is derived. As all events must happen, they are multiplied with each other as shown in Eq. (22).

$$P_{2,FO,2} = \left[P_{fo} * \left(0.5 * P_f * B * L\right)\right] * \left(P_{fw} * B * H\right) * P_{fo} \\ = 0.5 P_f P_{fo}^2 P_{fw} B^2 LH \tag{22}$$

For simplicity, P_{fw} is considered to be constant, but it can easily be understood that this is not realistic. Fire walls might be penetrated to allow for pipes to pass through and others can contain parts for passage from one to another compartment resulting in a higher P_{fw}.

The total loss rate of a fire that started in compartment one is given by Eq. (23).

$$R_{scenario\ 2} = S_{2,FO}(P_{2,FO,1} + P_{2,FO,2}) \tag{23}$$

Because the fire can start in compartment one or two the annual total loss rate, assuming immediate reconstruction after an event, is the summation of both, identical, scenarios as shown in Eq. (24).

$$\begin{aligned} R_2 &= 2\left[S_{2,FO}\left(P_{2,FO,1} + P_{2,FO,2}\right)\right] \\ &= 2 * 0.5 S_{1,FO}\left(0.5 P_{1,FO,1} + P_{2,FO,2}\right) \\ &= S_{1,FO}\left(0.5 P_{1,FO,1} + 0.5 S_{1,FO} P_f P_{fo}^2 P_{fw} B^2 LH\right) \\ &= S_{1,FO}\left(0.5 P_{1,FO,1} + 0.5 S_{1,FO} P_{1,FO,1} P_{fo} P_{fw} BH\right) \\ &= 0.5 R_1 * \left(1 + P_{fo} P_{fw} BH\right) \end{aligned} \tag{24}$$

Based on Eq. (24) the conclusion was made that the maximum loss rate reduction is half of that of the reference state. This situation occurs if the rate of failure of the fire wall P_{fw} is equal to zero. The latter being only a theoretical scenario.

1.6.3. Four compartments

For the building type with four compartments the previous example only shows the end formula:

$$R_4 = 4 * \frac{1}{16} * P_f P_{fo} S B^2 L^2 \left[1 + P_{fo} P_{fw} H \left(\frac{B}{2} + \frac{L}{2}\right) \\ + \left(P_{fo} P_{fw}\right)^2 H \left(\frac{B}{2} + \frac{L}{2}\right)\right] \tag{25}$$

Since $R_1 = P_{fo} P_f S B^2 L^2$ this leads to Eq. (26).

$$R_4 = 0.25 * R_1 \left[1 + P_{fo} P_{fw} H \left(\frac{B}{2} + \frac{L}{2}\right) + \left(P_{fo} P_{fw}\right)^2 H \left(\frac{B}{2} + \frac{L}{2}\right)\right] \quad (26)$$

Based on Eq. (26) the conclusion was made that the loss rate can be reduced to 25 percent of the reference state. In Appendix A an attempt was made to trace back the steps that preceded Eq. (26).

1.6.4. Example

The following example was provided to illustrate how the model can be used to identify the most effective safety measure. A comparison between four different risk strategies is made, see Table 1 [17].

Table 1: Different scenarios, comprising of different safety installations, are used to determine the most cost-effective risk strategy

scenario	*specification*
1	no compartmentalization, no sprinkler
2	no compartmentalization, sprinkler
3	two compartments, no sprinkler
4	four compartments, no sprinkler

Table 2 shows the data of the building layout and the boundary conditions in which the different scenarios will be applied. The values are an estimate of the previous author, based on literature and self-experience. It should be noted that the previous example does not contain any references and thus the validity of Table 2 is questionable.

Table 2: Parameters, indicators and values used to define a realistic setting for the different scenarios

parameter	*Indicator*	*unit*	*value*
B	Width	[m]	50
L	Length	[m]	100
H	Height	[m]	5
S	Value per unit floor area	[euro/m2]	1000
P_f	Frequency of ignition per unit floor area	[m-2yr-1]	5*10-6
P_{fo}	Probability of FO without sprinkler	[-]	0.2
$P_{fo,spr}$	Probability of FO with sprinkler	[-]	0.02
P_{fw}	rate of fire wall failure	$[1/\mathrm{m}^2_{\text{fire wall}}]$	5*10-4
$c_{0,spr}$	Installation cost sprinkler	$[\text{euro}/\mathrm{m}^2_{\text{floor area}}]$	40
$c_{0,comp}$	Installation cost fire wall	$[\text{euro}/\mathrm{m}^2_{\text{fire wall}}]$	100

Scenario one indicates the reference state and the total risk can be calculated with Eq. (18). For scenario two the same formula can be used, but the rate P_{fo} changes from 0.2 to 0.02. The total risk for scenario three and four can be calculated with respectively Eq. (24) and (26).

Table 3: Results of the risk calculation with the previous model and the selection of the most efficient strategy based upon the payback time

Scenario	*Risk R_i [euro/yr]*	*Risk reduction ΔR [euro/yr]*	*Installation cost C [euro]*	*Payback time $T = \frac{C}{\Delta R}$ [yr]*
1	$R_1 = 25{,}000$	/	/	/
2	$R_2 = 2{,}500$	$\Delta R_2 = R_1 - R_2 = 22{,}500$	$C_2 = c_{0,spr}BL = 200{,}000$	$T_2 = 9$
3	$R_3 = 12813$	$\Delta R_3 = R_1 - R_3 = 12{,}187$	$C_3 = c_{0,comp}BH = 25{,}000$	$T_3 = 2$
4	$R_4 = 6481$	$\Delta R_4 = R_1 - R_4 = 18{,}519$	$C_4 = c_{0,comp}H(B + L) = 75{,}000$	$T_4 = 4$

Based on the table above the conclusion was made that scenario three is the most profitable one for the given boundary conditions

1.6.5. Limits of the applicability and possible improvements of the old model

Possible fire spread paths depend on both the chosen ignition location and the final loss compartment, to counteract the amount of non-interchangeable scenarios the following assumptions were made in the old model:

- The compartments are equal in size
- The compartment value per m^2 is equally distributed over all the compartments
- A maximum number of four compartments is considered
- The fire can only travel further away from the source (see also Appendix A)
- The fire barriers are identical throughout the building

A graphical representation of the restrictions in the old model and the expected possibilities of the new are illustrated in Figure 4.

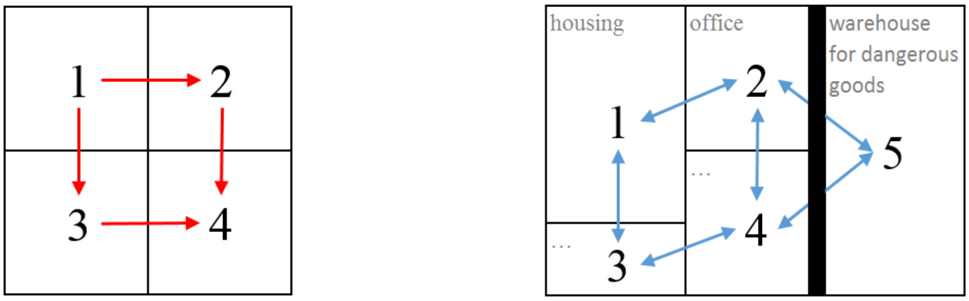

Figure 4: Graphical representation of the restriction by symmetry conditions in the old model versus the possibilities in the new model

The effect on the amount of scenarios would be noticeable, Table 4 shows the impact of not considering symmetry and adding one compartment. Calculating the exact number of scenarios is a prerequisite for a viable CBA, as each scenario introduces an extra cost.

Table 4: The effect of not assuming symmetry conditions and adding one compartment on the number of scenarios

Non-interschangeable scenarios in the old model ***5***	*Non-interchangable cenarios in the new model* ***68***				
1	1	1-2	1-2-4	1-2-4-3	1-2-5-4-3
1-2	2	1-3	1-2-5	1-2-4-5	1-3-4-2-5
1-3	3	2-1	1-3-4	1-2-5-4	1-3-4-5-2
1-2-4	4	2-4	2-1-3	1-3-4-2	2-1-3-4-5
1-3-4	5	2-5	2-4-3	1-3-4-5	2-5-4-3-1
		3-1	2-4-5	2-1-3-4	3-1-2-4-5
		3-4	2-5-4	2-4-3-1	3-1-2-5-4
		4-2	3-1-2	2-5-4-3	3-4-5-2-1
		4-3	3-4-2	3-1-2-4	4-3-1-2-5
		4-5	3-4-5	3-1-2-5	4-5-2-1-3
		5-2	4-2-1	3-4-2-1	5-2-1-3-4
		5-4	4-2-5	3-4-2-5	5-2-4-3-1
			4-3-1	3-4-5-2	5-4-2-1-3
			4-5-2	4-2-1-3	5-4-3-1-2
			5-2-1	4-3-1-2	
			5-2-4	4-5-2-1	
			5-4-2	5-2-1-3	
			5-4-3	5-2-4-3	
				5-4-2-1	
				5-4-3-1	

The old model doesn’t attempt to make a probabilistic assessment of the various parameters, and the following variables are assumed to be constant, or are not considered at all:

- Frequency of ignition (constant)
- Probability of ignition to grow to a local fire (not considered)

- Probability of flashover (constant)
- The failure probability of the compartmentation wall (constant)
- Firefighting measures (not considered)
- Time aspect of the fire (not considered)

Nevertheless changing the dimensions of the compartments will have a drastic influence on all these parameters, and the probabilistic risk assessment of them will be a crucial part in this thesis.

Whereas the old model neglected the time value of money, it will proof vital to incorporate the discount rate in the new model, in order to allow for rational decision making on obtained results.

In this thesis and in the old model only internal fire spread is considered, which excludes fires originating in the immediate proximity of the exterior boundaries, see Figure 5 left. Including these events is difficult because they are usually the result of arson, in which case the used ignition rates, fire growths and other equations of this thesis are not representable anymore. Nevertheless, these events occur and the private investor can decide to install further protection measures for safeguarding his business. The model presented can include the extra scenarios from an exterior fire, by including an additional compartment representing the surroundings of the building, see Figure 5 right. It should be noted that extra research would have to be conducted to determine the various parameters from Chapter 2 to represent an exterior arson fire. The values would then have to be hardcoded for compartment 5 and for the fire spread paths indicated in red. Furthermore, the CBA would have to be conducted to establish if the extra investment is beneficial.

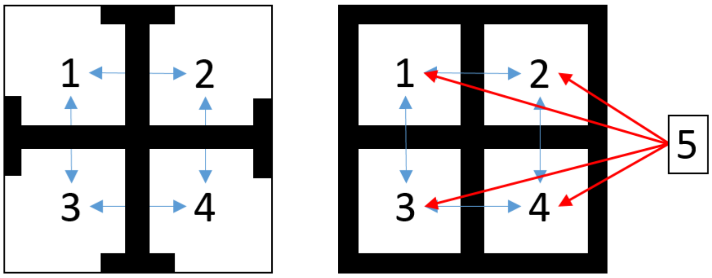

Figure 5: Left: schematic representation of how compartmentation is applied in this thesis, i.e., without considering exterior fires. Right: schematic representation of the impact of considering exterior fires and how to program the model to return the additional scenarios

The following assumptions are considered to be reasonable and are reused:

- There is only significant damage when flashover occurs
- There is no damage to adjacent compartments if the safety measure is successful
- When FO occurs, everything in the compartment is lost

1.7. Objectives of the thesis

The scope of this thesis will be to construct a model that allows for a probabilistic risk assessment to be conducted for compartmentalized buildings. With the resulting CBA, it will be possible to explicitly demonstrate if compartmentation is beneficial for the private investor. The following objectives are pursued:

- Researching the available literature and identifying a hands-on approach for probabilistic evaluation of fire hazards and active and passive measures, see Chapter 2
- Introducing a new mathematical method to identify all possible fire spread scenarios in a compartmentalized building, and thus allowing for an accurate estimate of the damage cost, see Chapter 3.
- Programming the above in a mathematical program, making it possible to conduct the CBA for various examples with only the need of changing the input parameters, Section 3.5.
- In Chapter 4 the new model is demonstrated on well thought of examples in order to: make a comparison with the previous model, draw conclusions for an effective compartmentalization of buildings, compare the costs and benefits of sprinklers and compartmentalization, compare the costs and benefits of various compartmentalization materials

Chapter 2

Theoretical aspects of flashover in a probabilistic context

In the following sections the various events and parameters propagating the onset of FO are accurately identified and quantified in a probabilistic risk assessment, a crucial aspect of this thesis as the probability of FO is the main parameter for the CBA, and eventually the new model.

Various definitions of FO exist, of which two are relevant ones for the new model:

- Walton and Thomas [16] define flashover as the transition of a growth stage to a compartment fire that includes the whole floor area of the enclosure, as a result $a_f = A_f$ and the fire transitions from fuel-controlled to ventilation-controlled [19].
- Peacock et al. [20] defines FO as the occurrence of a critical imposed heat flux of 20 kW/m^2. The latter is present when the gas temperature reaches 500°C, assuming the smoke layer is a perfect black-body. It must be noted that there is significant uncertainty in these numbers as they depend on the involved materials and the room configuration.

2.1. Frequency of ignition

For the new model ignition is addressed based upon a statistical method and not on its chemical aspects. De Sanctis [3] and NEN6079:2016 [2] refer to Ramachandran [21] who uses the floor area of the enclosure A_f to derive a statistical probability for ignition. The floor area is assumed to represent the number of ignition sources or occupants in the building. In the paragraphs below the method from NEN6079:2016 [2] is described in detail.

Eq. (27) and (28) relate the floor area of the enclosure with the ignition rate for respectively industrial buildings and other non-residential buildings.

$$F(A_f) = k_1\sqrt{A_f} \tag{27}$$

$$F(A_f) = k_2 \ A_f \tag{28}$$

The parameter k is based on fires reported, witnessed and suppressed to/by the fire services, referred to as "*potential serious initial fires*". Data from the Natural Fire Safety Concept, NEN-

EN 1991-1-2, the CBS, the International fire Engineering Guidelines (IFEG) and the method from Ramachandran [22] were compared by NEN6079 to come to the values listed in Table 5.

Table 5: Values for k_1 and k_2 to define the ignition rate in function of the total floor area. Reproduced from [2]

Variable	*Indicator*	*unit*	*Suggested Value*
k_1	Industrial buildings	$[m^{-1}yr^{-1}]$	10^{-3}
k_2	Other non-residential buildings	$[m^{-2}yr^{-1}]$	10^{-5}

De Sanctis [3] also refers to the approach of Fischer [23] as the floor area doesn't include significant building characteristics (e.g., the age of the building, level of maintenance, housekeeping, occupant characteristics). Fischer uses the volume V or insured value ν of the building. The model is mathematically represented by Eq. (29) and (30) and the valuation of its parameters is based upon Swiss insurance data, see Table 6. As Swiss cantonal insurance offices are obliged to ensure all buildings in the canton and include small fires, even where there is no interaction of the fire brigade, the data is considered to be representable for the ignition rate [3].

$$P(EX|x_0 = V) = \exp\left(\beta_{1,vol}\right) * vol^{\beta_{2,vol}} \tag{29}$$

$$P(EX|x_0 = v) = \exp\left(\beta_{1,\nu}\right) * \nu^{\beta_{2,\nu}} \tag{30}$$

Table 6: Values to describe the ignition rate in function of the volume or insured value as defined by Fischer et al. (2012). Reproduced from [3]

occupancy	$\beta_{1,vol}$	$\beta_{2,vol}$	$\beta_{1,\nu}$	$\beta_{2,\nu}$
Dwelling	-11.76	0.8700	-10.73	0.368
Office	-9.599	0.5277	-10.78	0.342
Retail	-8.979	0.4447	-15.51	0.714

As the ignition frequency described by Fischer provides more accurate results, it is the pursued approach in this thesis.

2.2. Probability of ignition to grow to a local fire

The probability that an ignition grows to a local fire P_{lf} is subdivided into $P_{1.0}$ and $P_{1.1}$ by NEN6079:2016 [2]:

- $P_{1.0}$ is the probability that takes into account the possibility of suppression by occupants or the fire service when the fire is still minimal. $P_{1.0} = 0.04$ is recommended.

- $P_{1.1}$ is a probability that takes into account extra measures, e.g., the removal of heat sources, use of non-flammable products instead of flammables, separation of ignition sources and flammable materials, etc.

As both events must happen for ignition to grow to a local fire the probabilities are multiplied as shown in Figure 6.

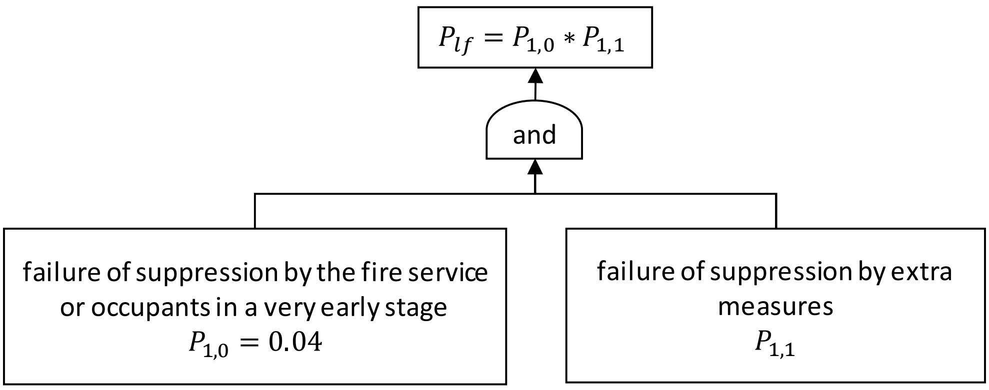

Figure 6: The different components that define the probability of ignition to grow to a local fire

$P_{1.1}$ can be determined by comparing the number of fires, ordered by cause, over a certain period versus the fictive number of fires that would still occur after implementing the extra mitigation measure. An example of the method is given in NEN6079:2016 [3, pp. 128-129].

2.3. The Heat Release Rate HRR

Under the influence of heat, a solid material starts to decompose and release volatiles, i.e., combustible gasses. The process of this phase change is termed pyrolysis and is accompanied by a mass loss of the item. Combustion of the gasses occurs if there is enough oxygen and heat available. The exothermic reaction releases heat and the heat release rate, HRR, of a single combustible material can be defined as followed [3]:

$$\dot{Q}(t) = \chi_c * \Delta h_c * \dot{m}'' * a_f(t)[kW] \tag{31}$$

In Eq. (31) there is only one-time dependent term, a_f, and the other parameters are assumed to be constant during a fire.

2.4. Fire growth with the αt² fire

The time it takes for a fire to reach a specific HRR will prove an important parameter for approximating the failure probability of the fire service in Section 2.9. Fire development is dependent on the configuration, availability and composition of the fuel packages in the enclosure. Meaning that, an endless amount of fire growth scenarios exists. Nevertheless, it is found that many fires have a growth rate that can be approximated by a parabolic curve [19]:

$$\dot{Q}_\alpha \ = \alpha t_\alpha^2 [kW] \tag{32}$$

Values for the fire growth coefficient α can be found in Table 7, and for other occupations in Appendix B.

Table 7: Values of α for different growth rates. Reconstructed from [18],[19]

Growth rate	*Typical scenario*	*α [kW/s²]*	*Time [s] to reach 1055 kW*
Ultra fast	High rack storage, PE rigid foam stacked 5 m high	0.19	75
Fast	PU mattress, PE pallets stacked 1 m high	0.047	150
Medium	Traditional mattress or armchair	0.012	300
Slow	Densely packed paper products	0.003	600

The first stated definition of FO allows to calculate the corresponding fire area a_f by dividing $\dot{Q}_\alpha$ with the heat flux for a fuel controlled fire $\dot{q}''_{fuel}$

$$a_f = \frac{\dot{Q}_\alpha}{\dot{q}''_{fuel}} \ [m^2] \tag{33}$$

It should be noted that the Dutch organisation TNO [24] derived equations that correlate alpha with the height of the stacked goods. For 11 m high, industrial storage buildings, the equations result in an increment with a factor 10 for α.

2.5. HRR needed to cause FO

The method developed by McCaffrey, Quintiere and Harkleroad [18] to predict the gas temperature of the upper layer in a pre-FO compartment lead to the following equation:

$$\Delta T = 6.85\left(\frac{\dot{Q}^2}{A_0\sqrt{H_0}h_kA_T}\right)^{\frac{1}{3}} \quad (34)$$

Substituting the FO definition of Peacock in Eq. (34) leads to the minimum HRR needed for FO to occur in the compartment:

$$\dot{Q}_{FO} = 610\left(A_0\sqrt{H_0}h_kA_T\right)^{\frac{1}{2}}[kW] \quad (35)$$

The experiments that led to Eq. (35) were conducted in a room with a height, floor area and opening area varying respectively from 0.3 m to 2.7 m, 0.14 m^2 to 12 m^2 and 0.03 m^2 to 1.9 m^2. The correlation should only be used for similar enclosures [25] and is thus not deemed useful for this thesis.

Another method is developed by Thomas, assuming that FO happens at a uniform upper layer temperature of 600°C [26]:

$$\dot{Q}_{FO} = 7.8A_t + 378A_o\sqrt{H_o}[kW] \quad (36)$$

Combining Eq. (32) and (36) results in the time to FO:

$$\dot{Q}_\alpha = \alpha t_\alpha^2 \Rightarrow \dot{Q}_{FO} = \alpha t_{fo}^2 \Leftrightarrow t_{fo} = \sqrt{\frac{\dot{Q}_{FO}}{\alpha}} \quad (37)$$

2.6. The maximum HRR for a ventilation-controlled regime

The airflow into an enclosure can be calculated with Eq. (38) [18].

$$\dot{m}_a = 0.5A_o\sqrt{H_o}\ [kg/s] \quad (38)$$

Assuming that a kilogram of oxygen used for combustion and the mass of oxygen in the air is respectively 13.1 MJ and 0.23 percent Eq. (38) can be rewritten to calculate the maximum HRR for a ventilation-controlled regime [27]:

$$\dot{Q}_v = 0.5 * 13100 * 0.23 A_o \sqrt{H_o} \approx 1500 A_o \sqrt{H_o} \; [kW] \tag{39}$$

Eq. (39) assumes that all the oxygen going into the compartment is used for combustion. This is an unlikely scenario, and the formula above gives thus a conservative prediction.

The openings in the enclosure must allow for enough energy, or oxygen, to enter for $\dot{Q}_v$ to increase up until $\dot{Q}_{FO}$. Once $\dot{Q}_v$ reaches $\dot{Q}_{FO}$ it is assumed that FO is initiated. In a mathematical formulation Eq. (40) states the first boundary condition that makes FO possible.

$$\dot{Q}_v \geq \dot{Q}_{FO} \tag{40}$$

2.7. Energy content available in the room

For large compartments, or compartments with small openings, the available oxygen in the room may allow for a higher HRR than predicted by Eq. (39). Staffansson [27] gives the following method to determine the time needed to release the energy content of a room.

The energy content available in the air of the compartment is mathematically represented by Eq. (41). To come to this expression the assumptions for Eq. (39) are reused, and it is assumed that combustion is possible until the mass of oxygen drops to 10 percent.

$$E = 13100 V (0.23 - 0.10) \rho_{air} \; [kJ] \tag{41}$$

The energy content can also be represented by Eq. (42).

$$E = \int_0^t \dot{Q}(t) dt \tag{42}$$

Combining Eq. (41) and (42) and assuming a constant HRR equal to $\dot{Q}_v$ results in the time needed to release E:

$$E = \dot{Q}_v * t \Leftrightarrow t_E = \frac{E}{\dot{Q}_v} \tag{43}$$

When t_E is sufficiently small, the energy content available in the room can be ignored since the fire will become ventilation-controlled fast. When t_E is sufficiently large it signifies that the fire may sustain a fuel-controlled HRR for a long time before becoming ventilation-controlled. It should be noted that Staffansson [27] lacks to give a value for when the time is sufficiently large or small.

Introducing a characteristic time t_{ch} a second boundary condition for FO can be formulated:

$$t_E \geq t_{ch} \tag{44}$$

In other words, when the condition of Eq. (40) is not fulfilled FO can still occur when the condition of Eq. (44) is met. An extra parameter $P_{poss,fo}$ is introduced here to summarize the boundary conditions that make FO possible or not.

$$\begin{gathered} if\ t_E > t_{ch}\ OR\ \dot{Q}_v > \dot{Q}_{fo} \Rightarrow P_{poss,fo} = 1 \\ if\ t_E < t_{ch}\ AND\ \dot{Q}_v < \dot{Q}_{fo} \Rightarrow P_{poss,fo} = 0 \end{gathered} \tag{45}$$

2.8. The maximum HRR for a fuel-controlled regime

It is assumed that the fire that leads to flashover when $P_{poss,fo} = 1$ has enough oxygen to burn all its volatiles and has a fuel-controlled HRR. Babrauskas [28] stated that these fires are comparable with free burning fires releasing a heat flux $\dot{q}''$ equal to the free burning maximum:

$$\dot{q}''_{fuel} \approx \dot{q}''_{free} = \chi_c * \Delta h_c * \dot{m}'' \tag{46}$$

Substituting Eq. (46) in Eq (31) leads to:

$$\dot{Q}_{fuel} = \dot{q}''_{fuel} * a_f(t) \tag{47}$$

Assuming that the fire can burn without intervention or decay and within the boundary condition of $t_E > t_{ch}$ or $\dot{Q}_v > \dot{Q}_{fo}$ it will eventually consume the total floor area A_f of the enclosure and have the maximum possible HRR for the enclosure $\dot{Q}_{fuel,max}$, represented by Eq. (48).

$$\dot{Q}_{fuel,max} = \dot{q}''_{fuel} * A_f \tag{48}$$

Given that $P_{poss,fo} = 1$ and A_f is a constant for a given compartment, $\dot{q}''_{fuel}$ will determine whether $\dot{Q}_{fuel,max}$ can reach $\dot{Q}_{fo}$, i.e., propagate the onset of FO.

In EN 1991-1-2 [29] values can be found for $\dot{q}''_{fuel}$, but the code lacks to give a reasoning behind the obtained data. From Table 8 it can be seen that all occupancies but the library have a $\dot{q}''_{fuel} = 250$ kW/m^2. De Sanctis [3] refers to Hosser [30] who interpreted this as the mean of a Normal distribution with standard deviation $\sigma = 50$.

Table 8: Fire growth rate and maximum rate of heat release RHR per m^2 (RHR$_f$) for different occupancies. Reconstructed from [7, p. 51]

Occupancy	*Fire growth rate*	t_α *[s]*	RHR_f *[kW/m^2]*
Dwelling	Medium	300	250
Hospital (room)	Medium	300	250
Hotel (room)	Medum	300	250
Library	Fast	150	500
Office	Medium	300	250
Classroom of a school	Medium	300	250
Shopping centre	Fast	150	500
Theatre (cinema)	Fast	150	250
Transport (public space)	Slow	600	250

De Sanctis [3] made a tentative model by representing the mass loss rate per unit area $\dot{m}''$, the heat of combustion Δh_c and combustion efficiency χ_c as random variables, respectively $\dot{M}''$, ΔH_c and X_c with their probability distribution type, mean value and coefficient of variation. His result showed a good correlation with the work of Hosser [30]. Due to the excellent correlation and the simplicity of a Normal Distribution, $X{\sim}N(250{,}50)$ is introduced in this thesis to represent the distribution of $\dot{q}^{"}_{fuel}$.

Figure 7 shows $X{\sim}N(250{,}50)$ and the inverse of its cumulative distribution function $1 - F_X(\dot{q}^{"}_{fo})$. The cumulative distribution function allows to assess the probability that $\dot{q}^{"}_{fuel}$ reaches the heat flux needed for flashover $\dot{q}^{"}_{fo}$:

$$P_{fuel} = \left[1 - F_X\left(\dot{q}^{"}_{fo}\right)\right] \, with \, \dot{q}^{"}_{fo} = \frac{\dot{Q}_{fo}}{A_f} \tag{49}$$

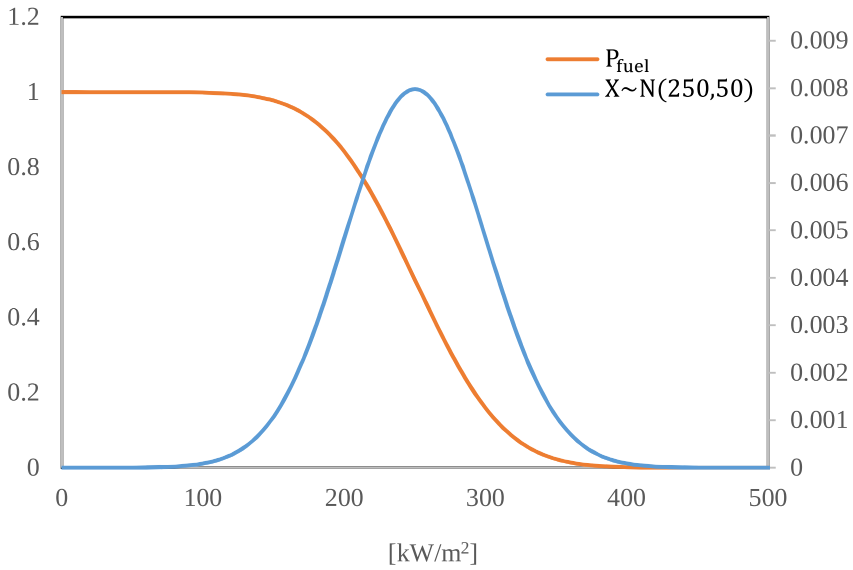

Figure 7: Probability density function $X{\sim}N(250{,}50)$ and the corresponding inverse cumulative distribution P_{fuel}, which describes the probability of the fuel-controlled heat flux reachomg the heat flux needed for flashover

Figure 8 shows $\dot{Q}_{fo}$ for two fixed opening dimension, $A_o * \sqrt{H_o}$, in function of the length of a square floor plan. Two points are marked, representing a floor area of 100 and 400 m^2. $\dot{Q}_{fo}$ for these points are respectively 5,000 and 14,000 kW. Increasing the floor area with a factor four leads thus to an increase of $\dot{Q}_{fo}$ by, approximately, three. Concluding that, with increasing floor area the term $\dot{q}^{"}_{fo}$ will decrease leading to a higher P_{fuel}. This might feel counterintuitive but is easy to understand as a bigger floor area means that there fuel is more fuel available to reach the HRR needed for FO.

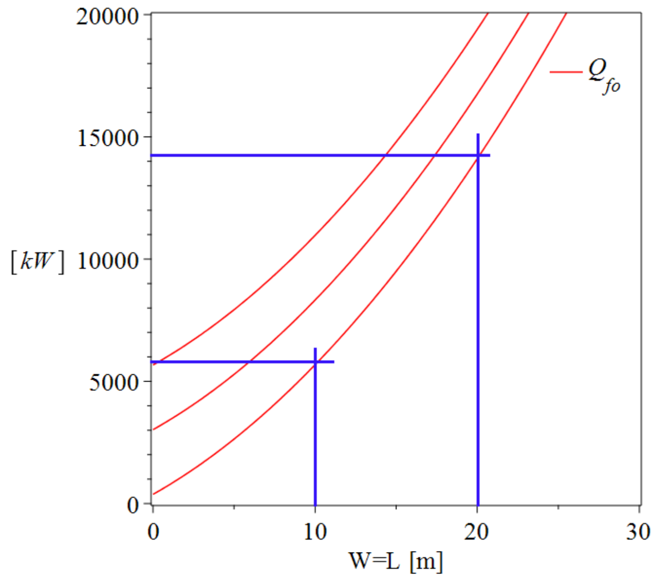

Figure 8: The HRR needed for FO $\dot{Q}_{fo}$ for a square floor plan and three different opening dimension, $A_o * \sqrt{H_o} = [1; 8; 15]$, in function of the length L

Using only P_{fuel} to estimate the probability of FO would lead to a gross overestimation as the time needed to get to $\dot{Q}_{fo}$ plays a vital role for the interaction capabilities of the fire service. How the probability for FO is corrected for time effects is elaborated in the next section.

2.9. Failure probability of the active measures

The goal of the fire service is in the first instance the safety of occupants and firemen and only after that the limitation of material losses. The fire-fighting services in the Netherlands defined four different suppression techniques, see Table 9.

Table 9: Different firefighting strategies in the Netherlands and the risk they oppose to the firefighter. Reconstructed from [2]

Risk level	*indicator*
<<	Defensive exterior attack
<	Offensive exterior attack
>	Defensive interior attack
>>	Offensive interior attack

The exterior defensive attack involves the least amount of risk as opposed to the offensive interior attack. Because of the associated risk the latter is, usually, only used in residential buildings where there is a great probability of occupants being trapped. The interior defensive attack is for other buildings where there is also a potential danger for occupants, e.g., hospitals, hotels, skyscrapers. For industry, the most common approach is the exterior attack. Nevertheless, the fire responsible at the scene will decide at the time of the event based upon the unique circumstances inherent to fire [2]. Because of the later, fire service intervention cannot be excluded with certainty, and a failure probability P_{suppr} is researched.

De Sanctis [3] refers to Davis [31] and Hosser [30] to describe the effectiveness of fire suppression. The control time has a positive correlation with the fire area a_f and a negative correlation with the amount of water available to suppress it. The larger a_f, the longer the time needed to control it. The more water available, the higher the flow rate can be, the shorter the control time. Davis [31] compared various (empirical) models available to describe the flow rate needed for effective suppression. The result showed that there was a substantial variation in the required flow rate. As such this method is not deemed reliable enough for this thesis.
Hosser [30] relates the probability of a successful suppression to the maximal controllable fire area a_{contr} of the fire brigade. Based upon fire-fighting experience a Normal Distribution, with a mean value of 200 m^2 and $\sigma = 40$ was proposed. The probability density function is denoted as $Y \sim N(200{,}40)$, see further Figure 10. The mean value is in accordance with Davis [31] who related an $a_{contr} = 200$ m^2 to a flow rate of 2500 l/min which is the typical capacity of the fire brigade in Switzerland. Due to the correlation between Davis [31] and Hosser [30] and the fact that the research is based upon actual fire-fighting experience this distribution is used to determine P_{suppr}. The application is explained in the next paragraph.

The average fire service response time, duration from time to call to time of arrival of the first vehicle at the scene, in England for 2016/17 was between eight and ten minutes [32]. De Sanctis [33] proposes that additional setup time, depending on the building characteristics, has to be added before the fire department can start its activities. In his conference paper, a Lognormal Distribution with a mean of 3.5 minutes is proposed. Based on the previous a, conservative, intervention time t_{int} of fifteen minutes is used for this thesis. In conjunction with the fire growth rates α, Section 2.1, the indicators shown in Table 10 can be calculated. The failure probability of the fire service P_{suppr} can then be estimated with the following methodology.
When the HRR needed for flashover $\dot{Q}_{fo}$, see Section 2.1, is bigger than the αt^2 HRR at

intervention time $\dot{Q}_{\alpha,t_{int}}$ it is assumed that FO did not occur and P_{suppr} is calculated based upon the fire area a_f, see Eq. (50). In case $\dot{Q}_{fo}$ is smaller than $\dot{Q}_{\alpha,t_{int}}$ it is assumed that FO did occur before the fire service is ready and thus P_{suppr} is calculated based upon the total floor area of the ignition compartment, see Eq. (51).

$$P_{suppr,before} = F_Y(Y, a_f) \tag{50}$$

$$P_{suppr,after} = F_Y\left(A_{f,i}\right) \tag{51}$$

Table 10: Calculation of the failure probability of the fire service for the ignition compartment based upon the αt^2 fire

Variable	*indicator*	*unit*	*Slow*	*Medium*	*Fast*	*Ultrafast*
α	Alpha	[kJ/s^3]	0.0029	0.012	0.047	0.188
t_{int}	Fire service intervention time	[min]	15	15	15	15
$\dot{Q}_{\alpha,t_{int}}$	HRR at t_{int}	[kW]	2,394	9,720	38,070	152,280
a_f	Fire area at t_{int}	[m^2]	10	39	152	609
$P_{suppr,before}$	Failure probability of the fire service upon arrival before FO	[-]	≈ 0	≈ 0	≈ 0.12	≈ 1
P_{act}	Failure probability of the active measures upon arrival before FO based upon a smoke detection system, Eq. (52)	[-]	≈ 0.25	≈ 0.25	≈ 0.34	≈ 1

Suppression by the fire service is only considered when there is a detection system installed [2]. Table 11 lists the failure probability of a thermal and smoke based system.

Table 11: Failure probability of different detection systems. Reproduced from [2]

Detection type	*Failure probability*
Thermal	0.062
Smoke	0.25

The probability of the detection system P_{det} and fire service have to be combined as shown in Figure 9.

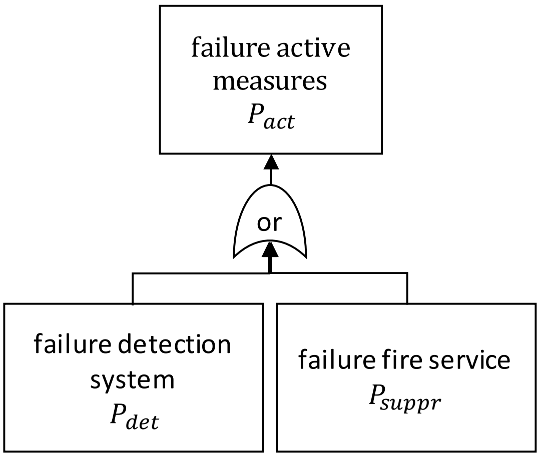

Figure 9: Schematic representation of the components that define the failure probability of the active measures

Eq. (52) shows the mathematical representation of Figure 9.

$$P_{act} = P_{det} + F_Y(A_f \; or \; a_f) - (P_{det} * F_Y(A_f \; or \; a_f)) \tag{52}$$

The components of Eq. (52) together with $Y \sim N(200{,}40)$ are plotted in Figure 10. As can be seen from the line for P_{act} there is always a probability that the fire department fails due to the dependency on the detection system.

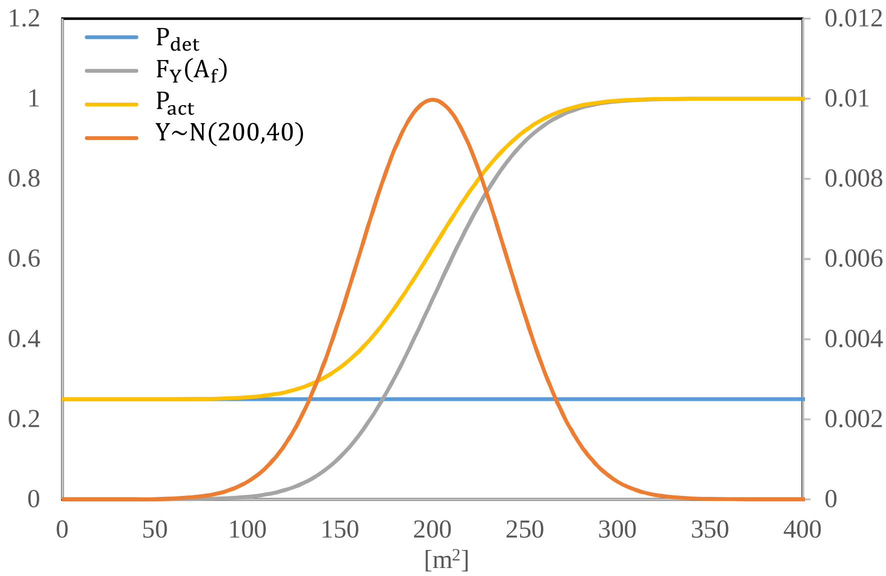

Figure 10: The different components that define the failure probability of the active measures together with the probability density function of Y

2.10. Probability of failure for compartmentalization wall after FO

De Sanctis [3] provides the following considerations about the failure probability of compartmentalization walls. Passive protection measures are part of the building's structure and are designed to keep specific performance criteria when exposed to the standard fire curve (ISO 834-1) for a given period. Failure is subdivided into three criteria:

- failing of the bearing capacity (R) due to the failing of the compartmentalization wall itself or the construction that it is connected to
- failing of the integrity (E) means that cracks appear through which flames can spread to the neighbouring compartment
- failing of the thermal insulation (I) or due to heat radiation (H) occurs respectively when the temperature of the not exposed wall is so high that objects in contact with it ignite (140 ℃ -180 ℃) or objects at a distance of 1 m ignite (500 ℃ - 600 ℃)

The performance can be assessed by evaluating the reliability with a limit state function [3]:

$$G = R_T - S_T > 0 \tag{53}$$

The complementary event or the failure probability of the passive protection element is expressed by Eq. (54) [3].

$$p_f = P(G \leq 0) = \int_{g(r_T, s_T)} f_{RS}\,(r_T, s_T) drds \tag{54}$$

The thermal exposure S_T is based upon the net heat flux to the element, and Fourier's law of heat flow allows to determine R_T, the thermal resistance. Due to the uncertainties associated with their calculation, R_T and S_T are introduced as random variables. De Sanctis [3] states that analytical solutions can only be derived in special cases, e.g., when the variables are Normal distributed (which is seldom the case). In general situations, the integral can be solved, depending on the problem, with integration techniques, simulation techniques (Monte Carlo) or by approximation methods (First or Second Order Reliability Method, FORM/SORM). Since the scope of this thesis is to provide an easy-to-use tool, another method is researched below.

NEN6079:2016 [2] provides a more fundamental way of looking at the failure probability and states the following factors that influence its value:

- $P_{fw,i\rightarrow j;con}$ is the failure probability of compartmentalization wall between comp. i and j, determined by the material used to make the separation
- $P_{fw,i\rightarrow j;pen}$ is the combined failure probability of all relevant penetrations in the compartmentalization wall between comp. i and j, determined by the level of detail administered in making the connection between the wall and intersecting elements

Figure 11 graphically illustrates the various steps that can lead to failure of a fire barrier.

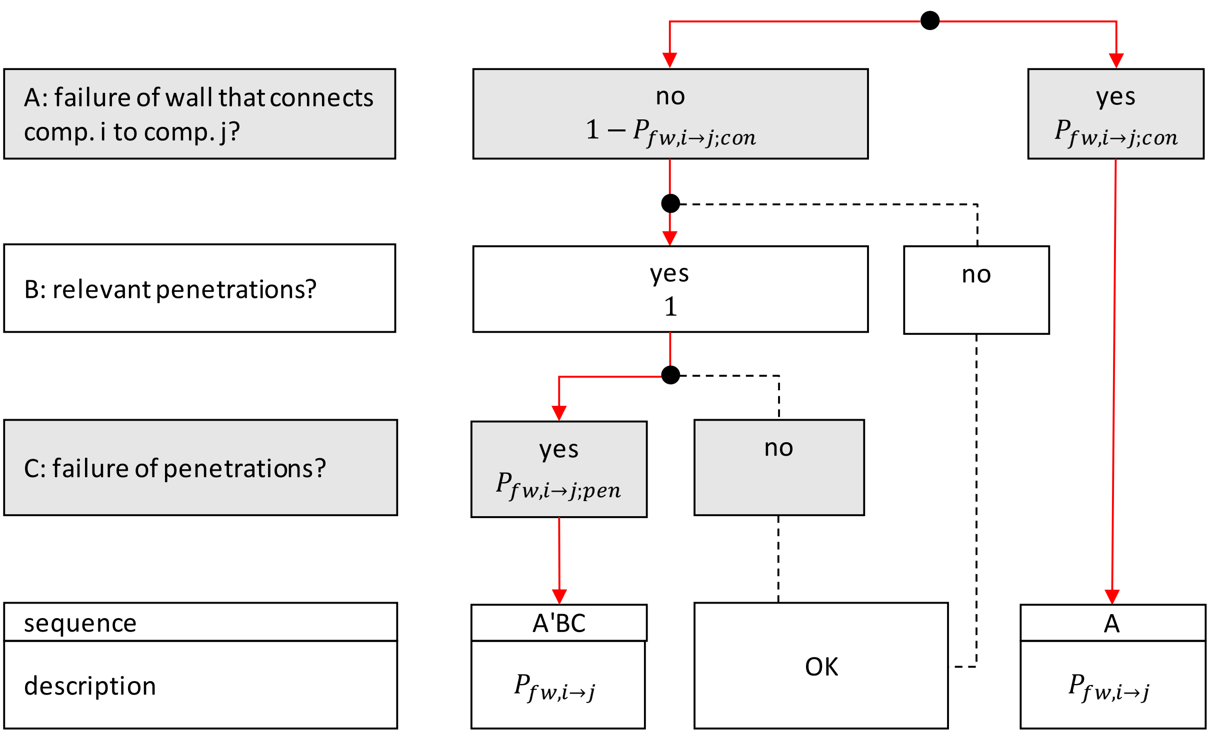

Figure 11: Different components to calculate the failure probability of a compartmentalization wall. Reconstructed from [2]

Based on Figure 11 tabulated data for the failure probability of the compartmentalization wall in function of the height, the fire resistance rating, the equivalent fire duration, building material and relevant penetrations is provided. Two such tables are presented below as an example, and the rest can be found in Appendix D.

Table 12: Failure probability of a brick compartmentalization wall with a height higher than 9 m and with NO relevant penetrations. Reconstructed from [2]

	REI [min]						
Equivalent fire duration [min]	*0*	*30*	*60*	*120*	*240*	*360*	*480*
30	1	**0.12**	0.06	0.04	0.03	0.2	0.01
60	1	0.74	**0.10**	0.06	0.04	0.03	0.02
120	1	0.98	0.74	**0.10**	0.06	0.04	0.03
240	1	1	0.98	0.74	**0.10**	0.06	0.04
360	1	1	1	0.98	0.74	**0.10**	0.06
480	1	1	1	1	0.98	0.74	**0.10**

Table 13: Failure probability of a brick compartmentalization wall with a height higher than 9 m and with relevant penetrations. Reconstructed from [2]

	REI [min]						
Equivalent fire duration [min]	*0*	*30*	*60*	*120*	*240*	*360*	*480*
30	1	**0.14**	0.14	0.14	0.14	0.14	0.14
60	1	0.87	**0.14**	0.14	0.04	0.14	0.14
120	1	1	0.87	**0.14**	0.14	0.14	0.14
240	1	1	1	0.87	**0.14**	0.14	0.14
360	1	1	1	1	0.87	**0.14**	0.14
480	1	1	1	1	1	0.87	**0.14**

It should be noted that NEN6079:2016 [2] states that there is a significant discrepancy between various sources. Warrington Delphi Uk and fire Engineering Guidelines Australia tabulate for a door in a concrete fire separation a failure probability of respectively 0.71 and 0.1. The basis for the tables in NEN6079:2016 comes from The Fire Protection Research Foundation.

To use these tables the calculation of the Equivalent time of fire exposure $\mathrm{t_{e,d}}$ is required. $t_{e,d}$ is used to relate the performance of structural elements, tested with the standard fire curve, to the actual boundary conditions of the compartment. The methodology, as explained in BS EN1991-1-2:2002 [29], is repeated in Appendix E.

The new model will calculate $\mathrm{t_{e,d}}$ for each compartment and automatically assume that each barrier has an REI equal to $\mathrm{t_{e,d}}$, in which case the constant value on the diagonal of the table can be used for all firewalls. The impact of $\mathrm{t_{e,d}}$ is then manifested in the CBA by assigning a higher implementation cost to walls that require higher REI. If the user wants to install a higher REI than required, the corresponding failure probabilities from the table can be defined individually per barrier, keeping in mind that the actual REI value should be equal or higher than $t_{e,d}$.

2.11. Probability of FO

The components determined from Section 2.1 to 2.10 are now combined to assess the probability of FO, which will be used in Chapter 3 as the main variable for the new model.

The probability for FO in a compartment is in NEN6079:2016 [2] based upon the mitigation measures present in that compartment. The risk strategy scenarios are:

- A no measures installed
- B special measures installed
- C active measures and/or fire department intervention are installed/possible

For Scenario A $P_{fo} = 1$ is advised.

Scenario B represents cases where a fire can be smothered due to a lack of oxygen. This is possible in small compartments with massive boundaries or underground compartments where there is a lack of oxygen, and the fire cannot create its own openings, e.g., by burning through the boundaries.
For cases where all doors and windows of the compartment are locked, $V < 300m^2$ and double glazing is installed $P_{fo} = 0.8$ is recommended. For other conditions, the probability has to be determined by the reviewer.

When Scenario C is applicable, a probability distribution has to be made of the different possible fire scenarios[3] as would be without mitigation measures. For each scenario, the effectiveness of active measure(s) has to be researched, and a timeline is to be constructed to determine the failure probability of the fire service. The probability of a scenario is then multiplied by the failure

[3] For simple boundary conditions a zone model can be used to assess the evolution of the fire in time. The model assumes a uniform upper hot gas layer and lower cold, i.e., ambient temperature, gas layer. The upper layer is feeded by a smoke plume rising from the fire source. NEN6079:2016 proposes the following models: TNO, Ozone or NPR-CEN/TR 12101-5.

probabilities of the mitigation measures and the summation over all scenarios is taken to get the total probability of FO.

NEN6079:2016 [2] only considers the probability of fire spread beyond the compartment and thus not the growth of a fire area bigger than the original compartment area. Also, this probability is only determined in detail for fire spread to neighbouring plots, i.e., not for internal fire spread. The reason being that the government doesn't want to intervene in private matters of the entrepreneur. It provides thus a minimum requirement, and the private investor is free to invest beyond that.

As the cost-benefit analysis in this thesis is done for the private investor and the goal is to make an easy-to-understand tool a different approach than a time-dependent zone model is followed, while considering internal fire spread and fire service intervention. The methodology is explained in the following section where it is assumed that FO is possible, i.e., $t_E > t_{ch}$ or $\dot{Q}_v > \dot{Q}_{fo}$.

2.11.1. FO in the ignition compartment

When $t_{int} < t_{fo}$ the risk of FO can be mitigated by the actions of the fire service, and thus the failure probability of the active measures has to be incorporated. In the other case, the fire service can't do anything anymore to prevent the event from happening, given that there is enough fuel in the compartment. The schematic representation of both situations can be seen in Figure 12 and Figure 13.

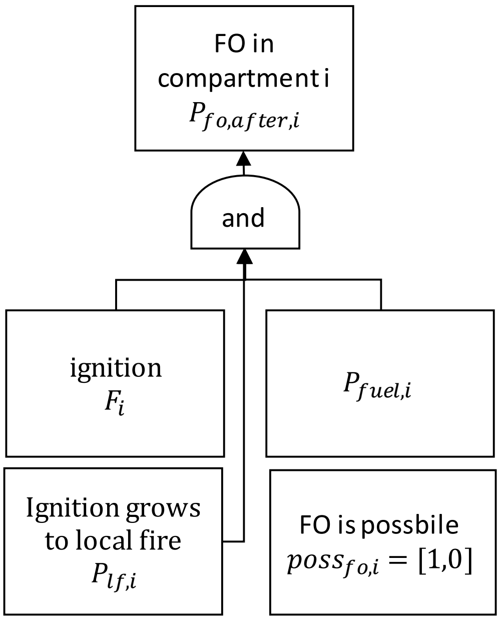

Figure 12: Annual probability of FO in the *ignition compartment* when the fire service arrives *after* FO

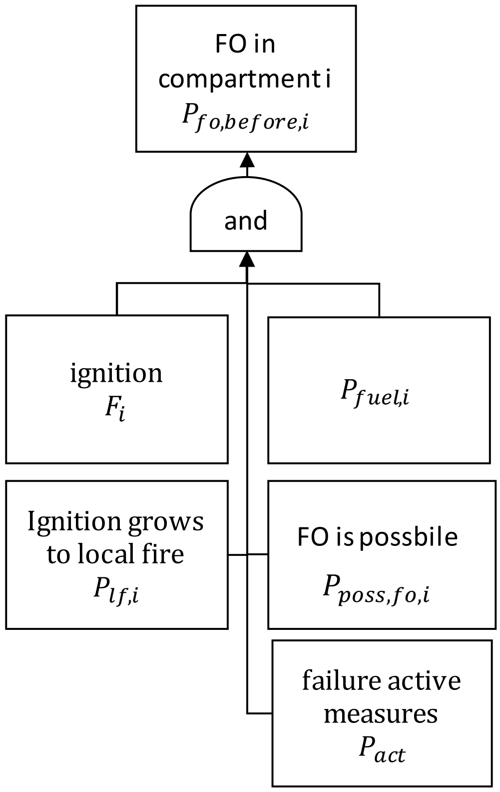

Figure 13: Annual probability of FO in *the ignition compartment* when the fire services arrive *before* FO

2.11.2. FO in compartment j adjacent to the ignition compartment

The probability that FO in comp i leads to FO in an adjacent compartment j is determined by the components illustrated in Figure 14 and Figure 15. When the fire service arrives after FO, the ignition compartment is already lost, and they can only intervene on the probability that the fire spread leads to FO, and thus a monetary loss, in the second compartment. In the other case, the intervention is already included in the FO probability of the ignition compartment.

Extra passive safety measures can refer to a floor plan that is designed in such a way that it removes fire load out of the vicinity of the fire wall. Making it less likely to have a failure due to the (E),

(I) or (H) criterion. The norm says that it's highly exceptional that extra passive safety measures are valid and thus the failure probability P_{pass} in this thesis is taken equal to one.

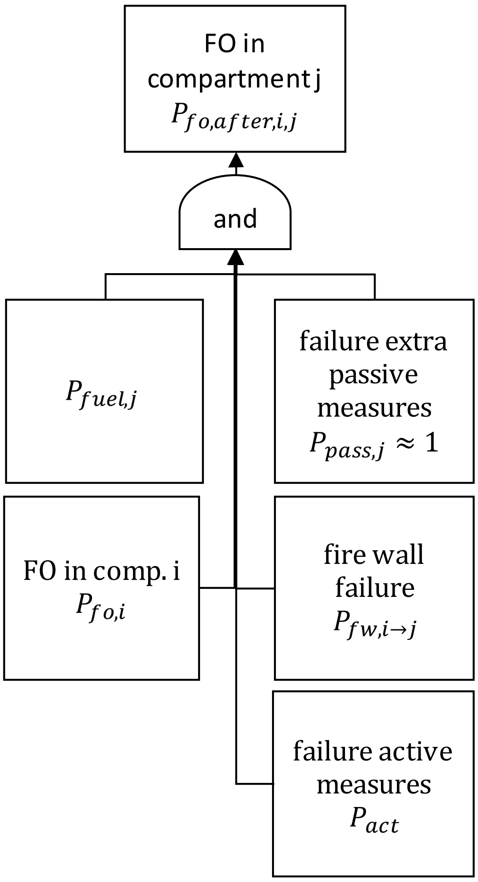

Figure 14: Annual probability of FO in *compartment j* when the fire service arrives *after* FO in compartment i

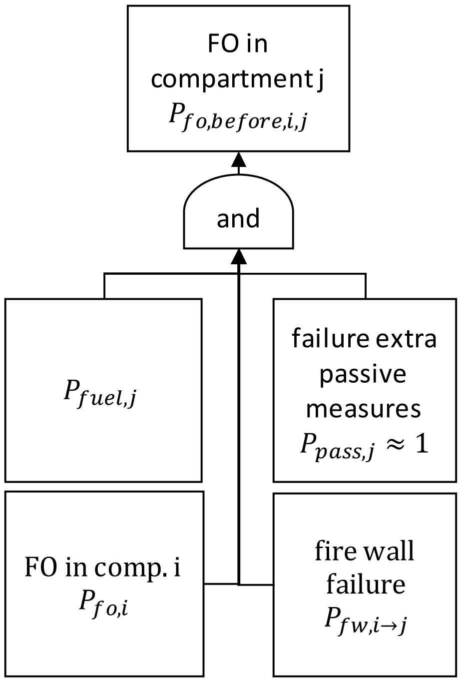

Figure 15: Annual Probability of FO in the *compartment j* when the fire services arrive *before* FO in compartment i

2.11.3. FO in a compartment k, at a certain distance from the ignition compartment i

In this thesis, it is not calculated how long it takes for the fire to penetrate a compartmentalization wall. As a consequence, it is not known with certainty if the second, third, etc. compartment already underwent FO before the fire service arrives. If it was the goal to construct a timeline of the fire spread a temperature-time profile would have to be constructed with the parametric time curves, as explained in NEN1991-1-2 [29], or with a computer model. From these curves, it would be possible to determine the temperature rise inside a solid in function of time and depth. The failure temperature and corresponding time can then be determined. This would make the model over complicated, and in addition, many more uncertainties would arise. The assumption is made that the fire brigade arrives before or after the ignition compartment reaches flashover but definitely before the second compartment reaches flashover. This is a reasonable assumption as approved document B [34] states that the minimum REI value for not sprinklered storage buildings, maximum height of 18 m, is 90 minutes. Meaning that the compartmentalization wall, in theory, should resist the fire for a much longer duration than the intervention time of the fire service. Making it unlikely that the second compartment undergoes FO before an intervention can be made.

Due to the stated assumption, the intervention for fire spread to a third compartment is already included in the ignition compartment or the compartment adjacent to the ignition compartment. The FO probability for compartment k is thus not dependent anymore on the intervention time of the fire service. Figure 16 shows the different components that define $P_{fo,i,j,k}$.

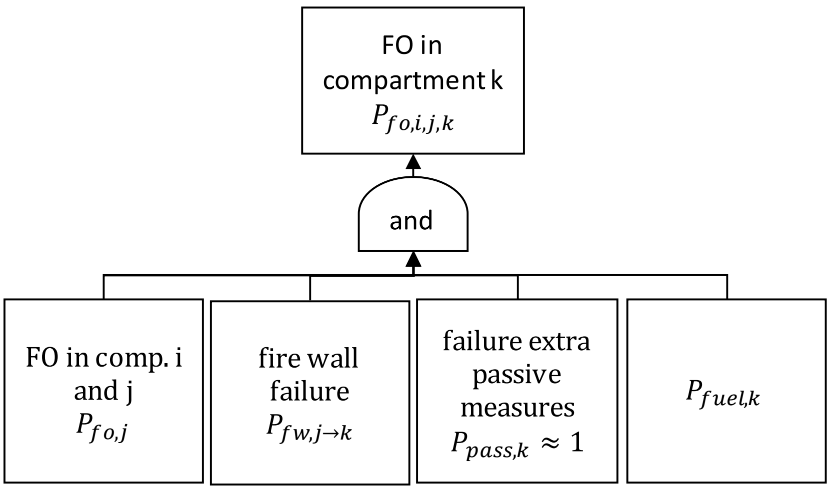

Figure 16: Annual probability of FO for a compartment not adjacent to the ignition compartment

Chapter 3

Development of the new model to calculate all possible fire spread scenarios and other parameters of the CBA

Since compartmentalization is the focus of this thesis the annual probability of failure with mitigation measure $P_{f,p}$ is the sequence of events that leads to FO. If the fire spreads from compartment 1 to 3 to 4 and is finally halted in compartment 6 the annual failure probability for that scenario will be denoted as $P_{fo,1,3,4,6}$. Section 3.1 explains the calculation method for $P_{f,p}$.
To determine the annual loss probability without mitigation measure $P_{f,0}$ a similar construct as for $P_{f,p}$ is followed in 3.2.
In Section 0 the calculation method of the discounted expected consequences is explained. Human casualties are expected to be non-occurring as in large logistic buildings the ratio employers per unit floor area is very low. Furthermore, the structures under consideration consist of only one storey which gives an extensive array of possible means of egress. For these reasons, fatalities and the associated monetary value are excluded from the CBA.

A complete overview of all the input parameters used for the model can be found in Appendix G.

3.1. Annual failure probability with mitigation measure

The total annual failure probability with compartmentalization installed can be determined with the following steps:

1) Specify a building layout
2) Chose an ignition compartment A
3) Chose a compartment B, at a certain distance from the ignition compartment
4) Determine all possible fire spread scenarios from A to B
5) Determine the annual failure, or loss, probabilities of all the scenarios
6) Repeat steps 1 to 5 until all compartments, except compartment B, have been identified as ignition place
7) Repeat steps 1 to 6 for a different compartment B under review until all compartments have been revised

8) Established that all these scenarios are unique and independent so that $P(A \cap B) \approx 0$
9) The total annual failure probability is the summation of the individual annual failure probabilities of all the scenarios

As possible scenarios depend on both the chosen ignition location and final loss compartment the total amount of potential fire spread scenarios rises exponentially with the number of compartmentalisations. Concluding that, the above steps can be "efficiently" done with hand calculations for two, three and, depending on symmetry and other boundary conditions, four compartments. Any more would be too time-consuming, and thus a mathematical model is constructed in the following sections.

3.1.1. Adjacency matrix

An adjacency matrix represents a finite graph in which a certain number of vertices are connected by a certain amount of acrc(s). When element $a_{i,j} = 1$ it means that vertice i is connected to vertice j and vice versa. For this thesis $a_{i,j} = 1$ signifies that fire spread is possible from compartment i to compartment j. To represent all possible connections the adjacency matrix will always be a square matrix with dimensions NxN, N being the amount of compartments. Figure 17 depicts a few possible building layouts with four compartments, $N = 4$. The adjacency matrixes AM for each arrangement is given in Eq. (55).

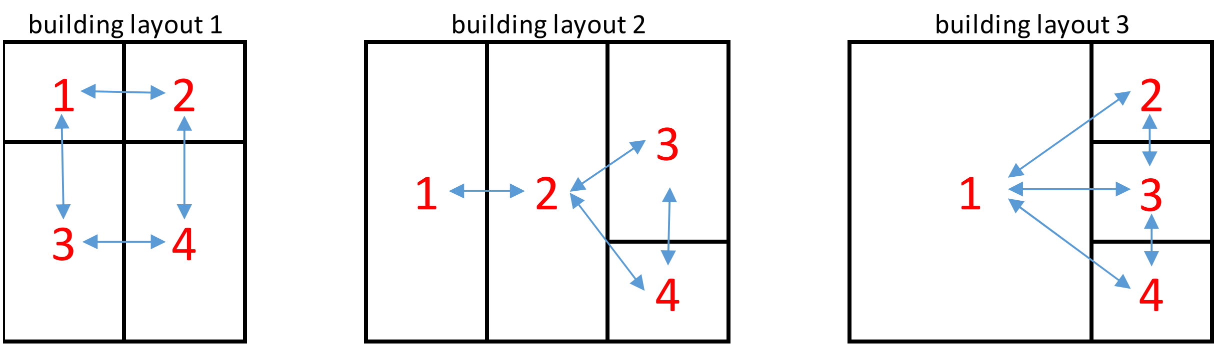

Figure 17: Non-exhaustive representation of building layouts with four compartments

$$B_1 = \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix} \quad B_2 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix} \quad B_3 = \begin{bmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix} \tag{55}$$

Possible finite graph interpretations of the different AM's are shown in Figure 18. The yellow numbers represent the compartments, and the blue arcs represent how fire can spread from one to another. It can be understood that the schematics in Figure 18 and Figure 17 represent the same building layouts.

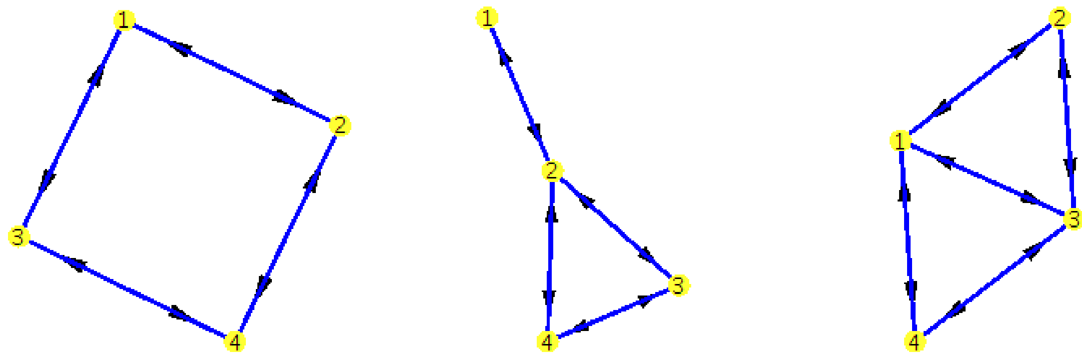

Figure 18: the mathematical representation of the adjacency matrix

The use of the adjacency matrix to determine the different scenarios and their annual failure probability is explained in the following section.

3.1.2. Using the adjacency matrix to determine all possible fire spread scenarios and their annual failure probability

Eq. (56) and (57) are the mathematical interpretation of Figure 13 and Figure 12 and represents the annual failure probability of ignition to grow to FO in any of the compartments where ignition can occur, parameter n_0.

$$for\ i\ \in n_0 \rightarrow P_{fo,before,i} = P_{poss,fo,i} * F_i * P_{lf,i} * P_{fuel,i} * P_{act} \tag{56}$$

$$for\ i\ \in n_0 \rightarrow P_{fo,after,i} = P_{poss,fo,i} * F_i * P_{lf,i} * P_{fuel,i} \tag{57}$$

Eq. (58) and (59) are the mathematical interpretation of Figure 15 and Figure 14 and represent the annual failure probability of all fire spread scenarios from the ignition compartment i to a compartment j, at a distance of one arc from i.

By specifying $B(i,j) = 1$ the characteristics of the AM are used to make sure that only compartments that are adjacent to, i.e., one arc removed from, compartment i are considered. Furthermore, the requirement $i \neq j$ prohibits that fire spreads to compartments that already underwent FO.

$$\begin{aligned} &for\ i\ \in n_0, 1 \leq j \leq N, B(i,j) = 1\ and\ i \neq j \\ &\rightarrow P_{fo,before,i,j} = P_{fo,before,i} * P_{fw,i\rightarrow j} * P_{pass,j} * P_{fuel,j} \end{aligned} \tag{58}$$

$$\begin{aligned} &for\ i\ \in n_0, 1 \leq j \leq N, B(i,j) = 1\ and\ i \neq j \\ &\rightarrow P_{fo,after,i,j} = P_{fo,after,i} * P_{fw,i\rightarrow j} * P_{pass,j} * P_{fuel,j} * P_{act} \end{aligned} \tag{59}$$

Eq. (60) calculates the annual loss probability of all scenarios that start at a compartment i and travel a distance of two arcs to compartment k, i.e., causes a loss in three compartments. The schematic representation is shown in Figure 16.

The requirements $B(i,j) = 1$ and $B(j,k) = 1$ make sure that compartment k is adjacent to compartment j and that compartment j is adjacent to compartment i. An extra condition $i \neq j \neq k$ is applied to make sure that fire cannot spread through compartments that already suffered FO.

$$\begin{aligned} &for\ i\ \in n_0, 1 \leq j,k \leq N, B(i,j) = 1, B(j,k) = 1\ and\ i \neq j \neq k \\ &\rightarrow P_{fo,i,j,k} = P_{fo,i,j} * P_{fw,j\rightarrow k} * P_{pass,k} * P_{fuel,k} \end{aligned} \tag{60}$$

Eq. (60) has to be expanded until it can describe the longest possible fire spread path for a given building layout.

Equations (59) to (63) were programmed in the mathematical software Maple together with the parameters N, n_0 and AM for a four compartment building layout. The output, i.e., the possible fire spread scenarios and their annual loss probability can be seen in Table 29 of Appendix F. Furthermore, it is checked if the model returns all scenarios in Figure 36 of Appendix F.

3.2. Annual failure probability without mitigation measure

The scenario without mitigation measure is, in essence, the same as the loss scenario for one compartment, Eq. (61). The only difference is that its parameters are calculated based upon the building's exterior dimensions instead of those of the compartment:

$$P_{fo,ext} = P_{poss,fo,ext} * F_{ext} * P_{lf,ext} * P_{fuel,ext} * P_{act} \tag{61}$$

Multiplying $P_{fo,ext}$ with the failure probability for sprinkler suppression P_{spr} will result in the annual loss probability for a building without compartmentalization but with sprinklers installed. The mathematical representation is shown in Eq. (62) and shall be used to compare the utility of compartmentalization with sprinklers.

$$P_{spr,ext} = P_{poss,fo,ext} * F_{ext} * P_{lf,ext} * P_{fuel,ext} * P_{act} * P_{spr} \tag{62}$$

The failure probabilities in Table 14 are provided by NEN6079 for sprinkler systems in function of the means of supply [2].

Table 14: Failure probabilities of various sprinkler systems. Reproduced from [2]

sprinkler type	*Failure probability*
Normal installation	0.02
Independent supply	0.01
Double independent supply	0.005

3.3. The present value of the consequences

Costs are preferably determined per compartment, either for the whole unit $s_{whole,i}$ or per unit floor area $s_{c,i}$. Nevertheless, it is sometimes outside of the control of the user how such data is delivered, and if costs are only known for a total loss of the building s_{event} they can be related to a compartment by using the ratio compartment floor area over the total building floor area. The total discounted consequences associated with a loss in a certain compartment i are then given by:

$$for\ 1 \leq i \leq N$$
$$\rightarrow S_i = \left(s_{whole,i} + s_{c,i} * C_{w,i} * C_{l,i} + \frac{C_{w,i} * C_{l,i}}{A_{ext,f}} * s_{event}\right) * \frac{1 - \exp(-\gamma t_u)}{\gamma} \quad (63)$$

Table 15 shows an example of how consequences can be attributed to a total loss, per unit floor area or per compartment. The totals can be used as input for Eq. (63).

Table 15: Example of direct and indirect costs associated with a loss in a compartment or for a total loss, reproduced from [35]

Type	*Subcategory*	s_{event} *[euro/fire]*	$s_{c,i}$ *[euro/m²/fire]*	$s_{whole,i}$ *[euro/fire]*
Supply chain	Production related Additional benefits due to extra sales	135.000 25.000		
Damage	Damage to own material/property		$comp.1 = 100$ $comp.2 = 1200$ $comp.3 = 500$ $\dots$ $comp.N = 300$	
Legal	Fines	10.000		
Insurance	Insurance premium	20.000		
Human and environmental	Recruitment	2.500		
other	Clean-up			$comp.1 = 200$ $comp.2 = 300$ $comp.3 = 500$ $\dots$ $comp.N = 100$
TOTAL		**192.500**	$\mathbf{comp.1 = A_{f,1} * 100}$ $\mathbf{comp.2 = A_{f,2} * 1200}$ $\mathbf{comp.3 = A_{f,3} * 500}$ $\mathbf{\dots}$ $\mathbf{comp.N = A_{f,N} * 300}$	$\mathbf{comp.1 = 150}$ $\mathbf{comp.2 = 800}$ $\mathbf{comp.3 = 500}$ $\mathbf{\dots}$ $\mathbf{comp.N = 200}$

A complete overview of possible direct and indirect costs can be found in Appendix C and can prove helpful to set up the input for the CBA when the goal is to include the total cost of the fire.

3.4. The present value of the expected consequences

The PV of the expected consequences, or risk, per compartment are obtained by multiplying the annual failure probabilities of each scenarios, calculated in Section 3.1, with the PV of the consequences associated with the final loss compartment:

$$
\begin{aligned}
&for\ 1 \leq i, j, k, l, \ldots \leq N \\
&\quad \rightarrow R_i = P_{fo,i} * S_i \\
&\quad \rightarrow R_j = P_{fo,j} * S_j \\
&\quad \rightarrow \cdots \\
&\quad \rightarrow R_{i,j} = P_{fo,i,j} * S_j \\
&\quad \rightarrow R_{j,i} = P_{fo,j,i} * S_i \\
&\quad \rightarrow \cdots \\
&\quad \rightarrow R_{i,j,k} = P_{fo,i,j,k} * S_k \\
&\quad \rightarrow R_{k,j,i} = P_{fo,k,j,i} * S_i \\
&\quad \rightarrow \cdots \\
&\quad \rightarrow R_{i,j,k,l,N} = P_{fo,i,j,k,l,N} * S_N
\end{aligned}
\tag{64}
$$

Summing up all equations in Eq. (64) results in the total PV of the expected consequences with compartmentalization installed or the damage cost $D(p)_{comp}$:

$$D(p)_{comp} = R_i + R_{i,j} + R_{j,i} + \cdots + R_{i,j,k} + R_{k,j,i} + \cdots + R_{i,j,k,l,N} + \cdots \tag{65}$$

Without safety measures the total PV of the expected consequence or the maximum possible benefit $B(p)$ is represented by the following equation:

$$B(p) = P_{fo,ext} * S_{ext} \tag{66}$$

$$with\ S_{ext} = \sum_{i=1}^{N} S_i$$

Eq. (67) follows the same approach to determine the damage cost in case of sprinkler installation without compartmentalization

$$D(p)_{spr} = P_{spr,ext} * S_{ext} \tag{67}$$

3.5. Flowcharts describing the steps from model input to output

Figure 19 shows the input parameters used to describe the building dimensions and openings. As the output is used for nearly all further calculations, see Figure 20 to Figure 24, this is the first step of the model.

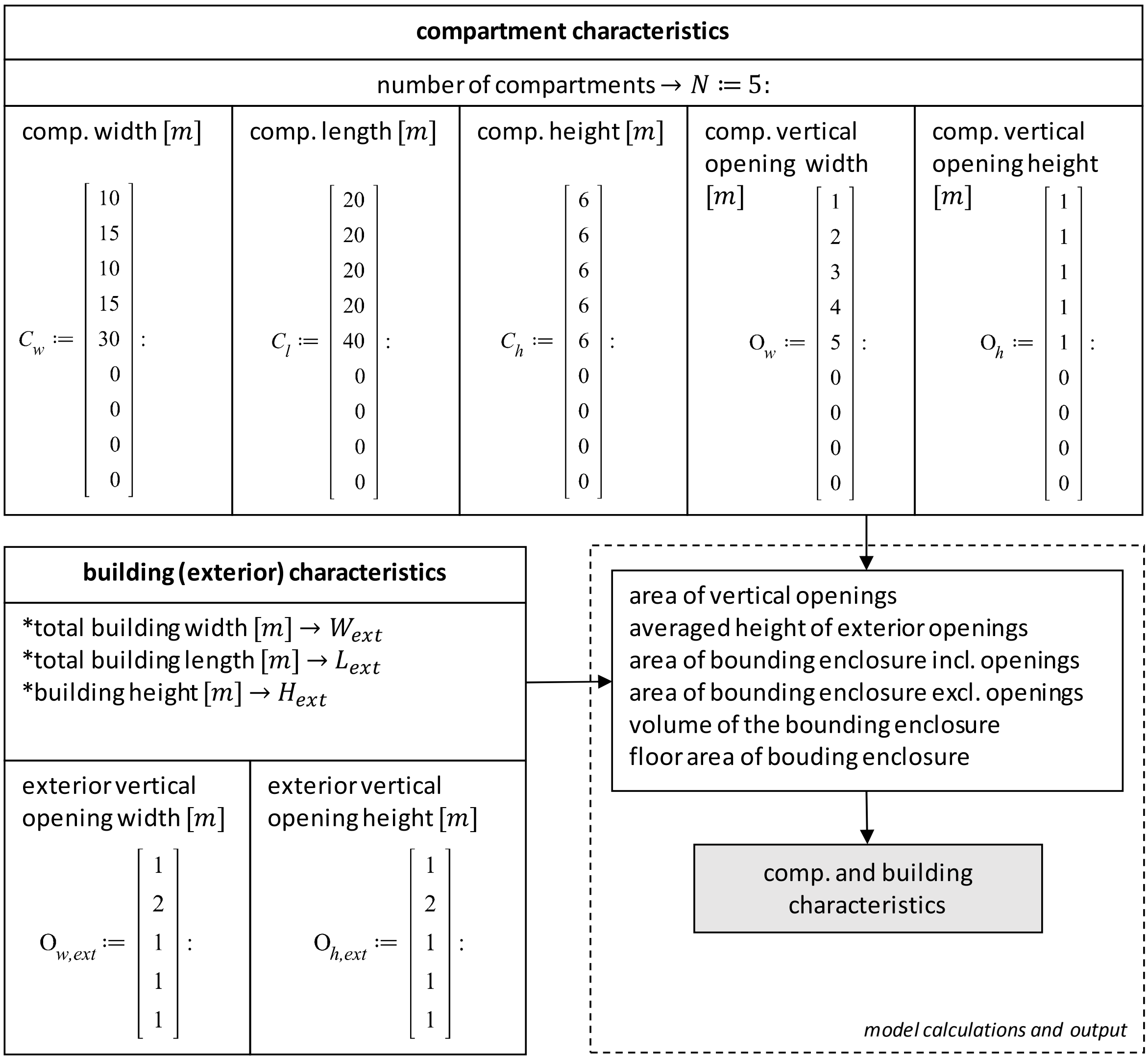

Figure 19: Using input to calculate the comp. and building characteristics

As explained in Section 3.1 three input parameters are needed to obtain the possible fire spread scenarios, see Figure 20. The output will mainly be used to calculate the annual failure probability, Figure 22, and the expected consequences per compartment, Figure 24.

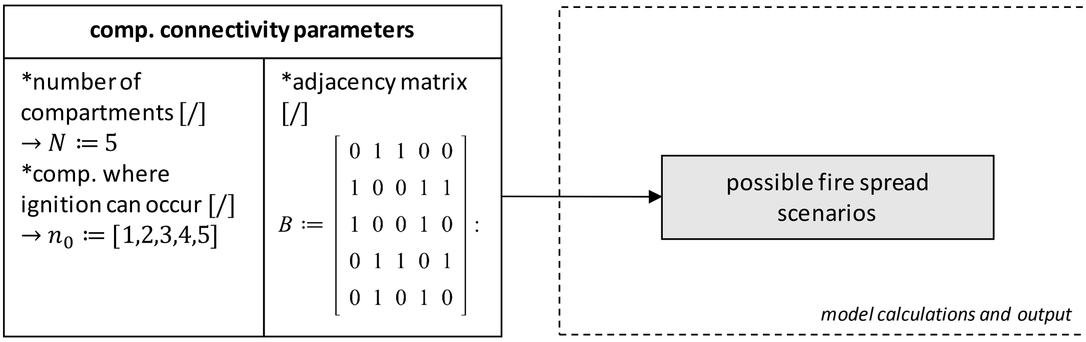

Figure 20: Using input to calculate the possible fire spread scenarios

Following the method from Section 2.1 and 2.2 the input parameters in Figure 21 are used to determine the frequency of ignition and the probability of ignition to grow to a local fire.

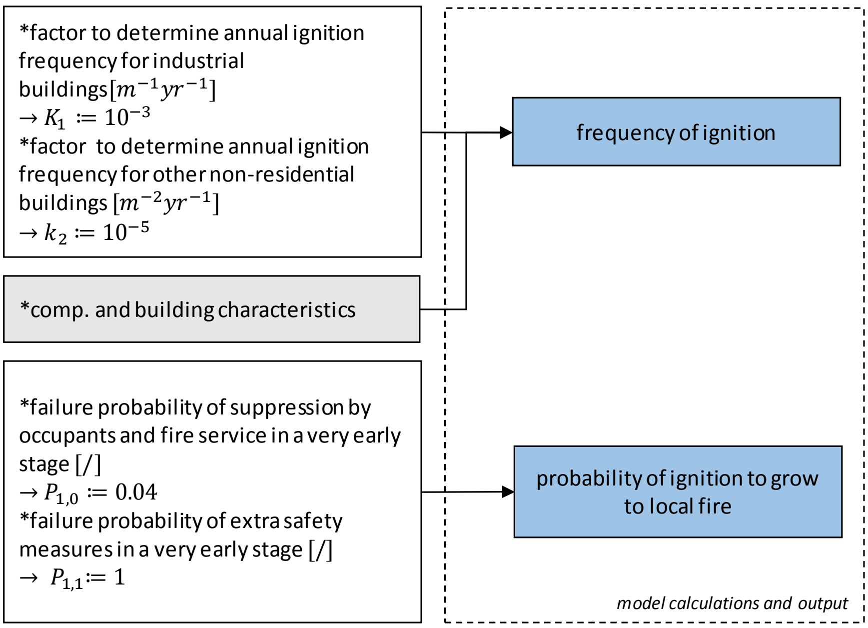

Figure 21: Using input to calculate the ignition frequency and the probability of ignition to grow to a local fire with and without mitigation measure

Figure 22 shows the various input parameters needed for the calculation of the equivalent time of fire exposure, see Appendix E. Once the times are obtained, they are rounded up to the closest standard REI value. This can then be used in conjunction with the tables provided in Section 2.10 to determine the failure probability of the fire wall under review. Furthermore, the required REI value for each compartment wall determines the installation price per unit wall area. Higher REI values require thicker insulation which leads to a higher material cost. The effect is taken into account with factors that relate the cost of a fire wall with a specific REI value to a chosen reference situation, e.g., $a_{REI,30} \coloneqq 1$.

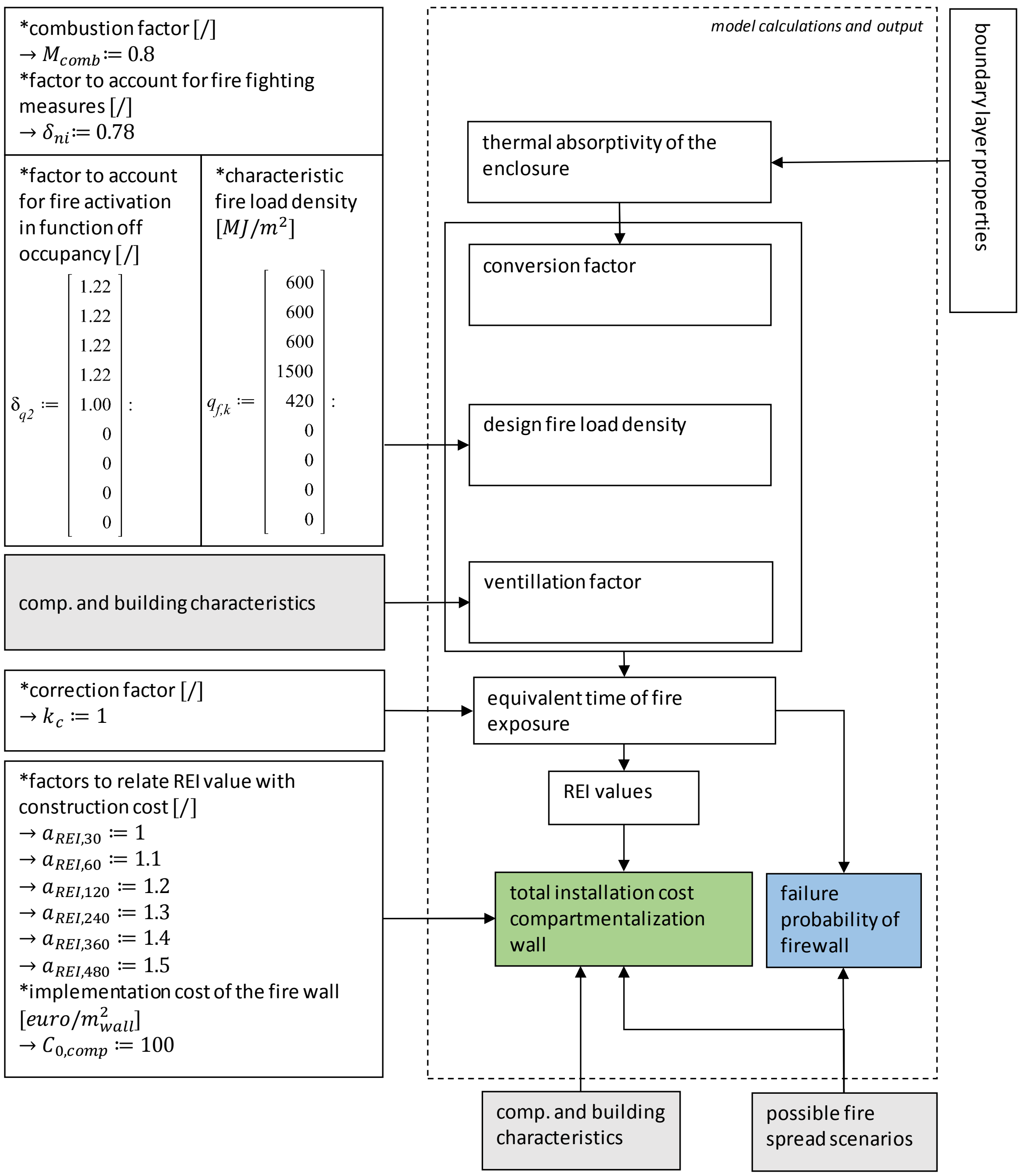

Figure 22: Using input to calculate the installation cost and failure probability of the fire wall

Figure 23 summarizes the components of Section 2.10 that define the HRR and lists them together with the input parameters needed to calculate the probability of FO.

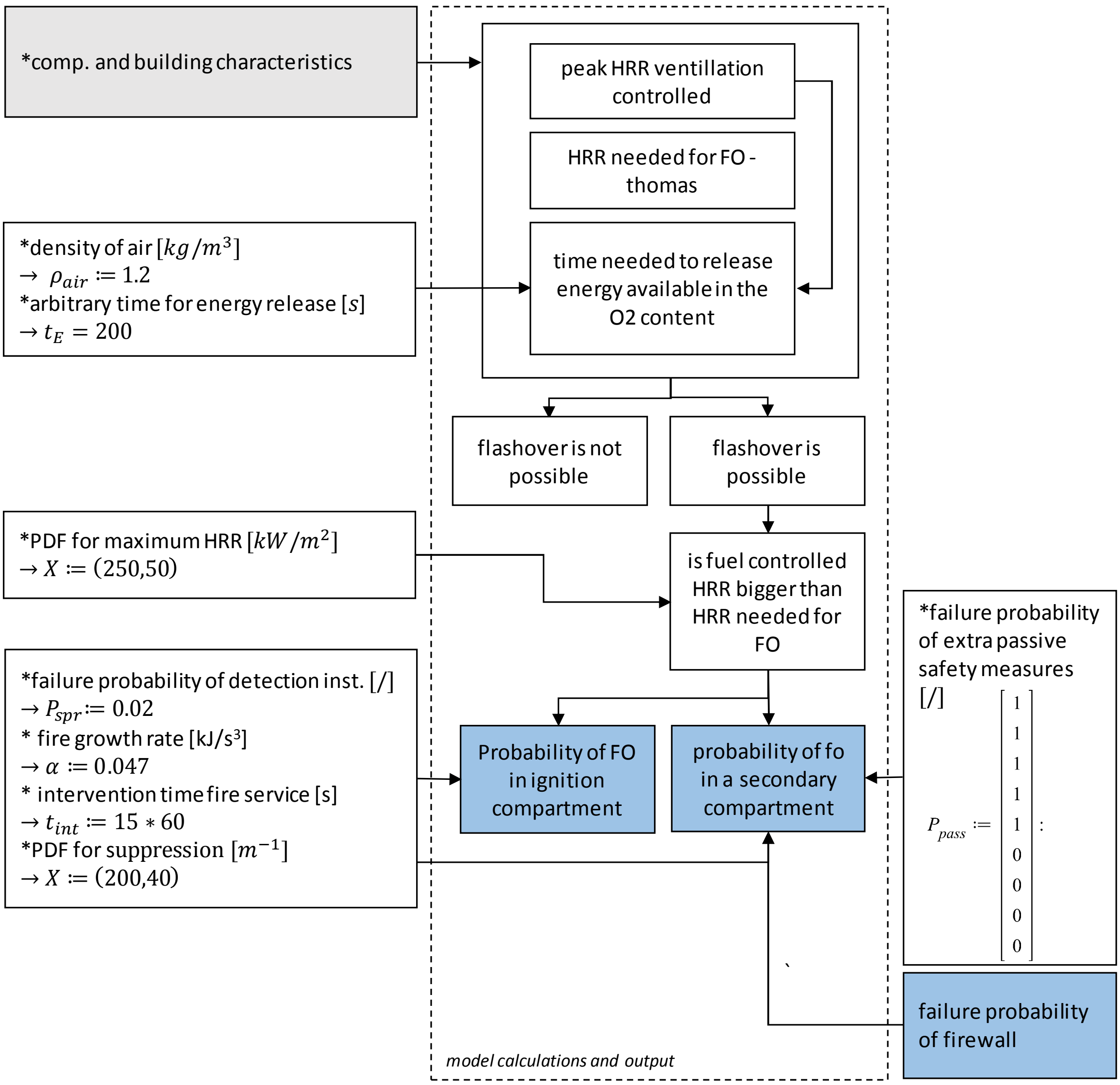

Figure 23: Using input to calculate probability for FO with and without mitigation measure

Using the calculated failure probabilities per compartment as input for the different scenarios the annual loss probability per scenario is obtained. Combining the latter with the parameters to describe the time effects and monetary value per compartment, see Sections 1.3.1, 3.3 and 3.4, leads to the total net utility as shown in Figure 24.

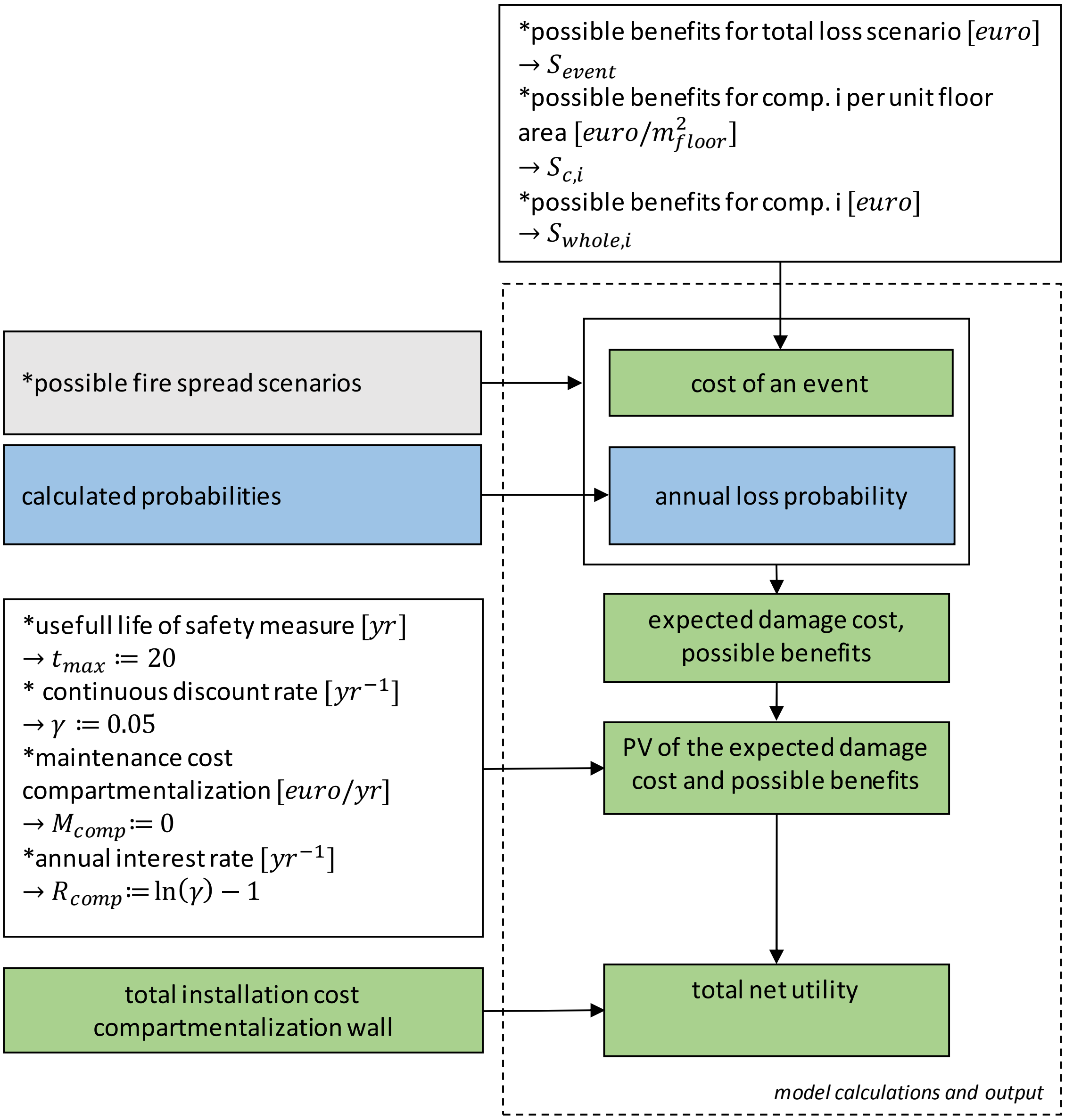

Figure 24: Using input to calculate the total net utility of the mitigation measure

Chapter 4
Results

4.1. Comparing the new model with the previous model

The previous model example, Section 1.6.4, is repeated in order to assess the effects of the various alterations made to the original model. The input data from Table 3 is reused except the probabilities for FO and the frequency of ignition. The complete tables with input and output can be found in Appendix H.

As the previous model doesn't consider cost discounting the comparison cannot be made upon absolute numbers and thus, orders of magnitude and trends are observed.
The lifespan of a non-residential building is estimated by the internal revenue service, IRS in America, to be 39 years [36]. This period is also deemed to be representative for the useful life of compartmentalization as it is part of the buildings infrastructure. Furthermore, a continuous discounting rate of 5% is used as the cost benefit analysis is done for the private investor.

The ignition frequencies obtained with the equations from NEN6079, Section 2.1, show a constant offset, see Table 16, and are thus used as they won't influence trends.

Table 16: comparison of the old and new values for the ignition frequency and the probability of flashover for the various scenarios

Scenario	$F(A)\ [yr^{-1}]$	
	Old	*New*
No mitigation measure	0.025	0.05
Sprinkler	0.025	0.05
2 comp	0.0125	0.025
4 comp	0.00625	0.0125

The results from both analyses are displayed in Table 17. The differences in installation costs are due to the fact that the new model uses cost scaling factors to account for the required REI values.

Both models indicate that the most expensive measure, sprinkler, results in the greatest risk reduction. Where the old model shows a negative correlation between risk and the number of compartments, i.e. the more compartments, the lower the risk and thus the safer the building. The results from the new model show an opposite trend. The four compartment building poses a greater risk than the two compartment layout.

Table 17: Cost-benefit results from the new and old model

scenario	*description*	*Risk R [euro/yr]*		*Risk reduction ΔR [euro/yr]*		*Installation cost C [euro]*		*Payback time*	
		Old	***New***	*Old*	***new***	*Old*	***New***	*Old* $\frac{C}{\Delta R}$	*New*
1	No measure	25,000	**58,335**	/	**/**	/	**/**	/	/
2	Sprinkler	2,500	**853**	22,500	**57,482**	200,000	**200,000**	9	∞
3	2 comp	12,183	**29,182**	12,187	**29,153**	25,000	**28,750**	2	38
4	4 comp	6,481	**43,276**	18,519	**15,058**	75,000	**86,250**	4	∞

There is no possibility to compare the payback time as the old model ignores the time effect of money and thus considers the risk reduction as a constant benefit happening every year. The new model effectively reduces the benefits earned in the future to a smaller fraction every successive year. The reasons for this are mentioned in Section 1.3.1. Figure 25 shows that the costs introduced by a sprinkler or four compartment installation outweigh greatly the possible benefits and thus the payback time is infinite. The two compartment model shows a positive net utility and the payback time, together with the IRR, can be determined numerically or from Figure 26, as explained in Section 1.3.3.

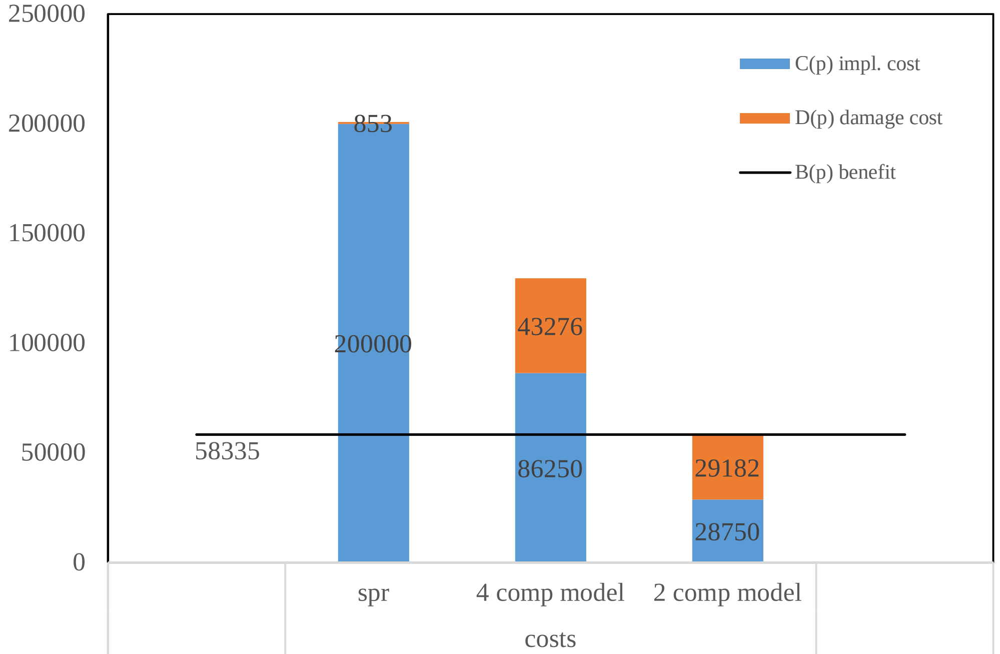

Figure 25: The costs and possible benefits for the two and four compartment and sprinkler model

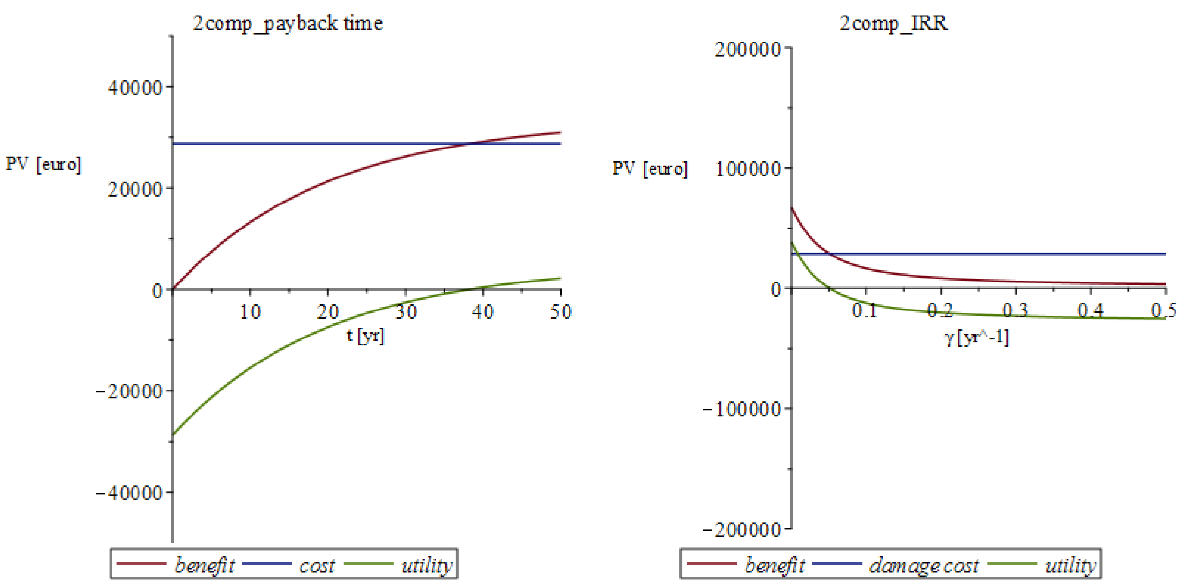

Figure 26: The benefits, costs and utility in function of the time, left, and discount rate, right, allows to determine respectively the payback time and internal rate of investment, IRR

The reason for the negative utilities and adverse trend can be found in the approach to determine the probability of flashover. The effect is further elaborated in the following section.

4.1.1. Explanation of the differences between the two models

The negative utility in scenario four is caused by the combination of three effects. Obviously the installation cost is far greater than scenario three, but even if this wasn't the case the building layout would still result in a negative cost-benefit analysis. The maximum possible benefits, scenario without mitigation measure, are calculated for a situation where the fire service arrives before FO. On the other hand, the damage cost per compartment is determined using a situation where the fire service arrives after FO. The resulting low benefits, due to a low P_{fo} for the building, are thus not balanced by a great risk reduction but even further unbalanced by higher damage costs, due to a high P_{fo} per compartment.
The benefits for scenario two are calculated in the same way but here the low benefits are balanced by a low damage cost due to the fact that the bigger compartments don't reach FO before the arrival of the fire service, meaning that P_{fo} for the building and compartments are identical.

The example indicates that there is an ideal compartment size. The corresponding dimensions would prolong flashover and allow a calculation of P_{suppr} on the fire area instead of the total floor area.

4.1.1.1. The effect of compartmentalization on the probability of FO

Based upon the HRR needed for flashover $\dot{Q}_{fo}$, the ventilation controlled peak HRR $\dot{Q}_v$ and the time needed to release the energy content of the room t_E the model calculates whether FO is possible or not, see also Eq. (44) and (49). The output table in Appendix H states that FO is possible in all compartments of the two scenarios as well as in the building without measure.

When FO is possible the two components that determine its probability are the failure probability of the active suppression P_{act} and the probability that $\dot{Q}_{fo}$ is smaller than the fuel controlled peak HRR P_{fuel}.

P_{act} is dependent upon the intervention time of the fire service, set to 15 min in Section 2.9, and the time to $\dot{Q}_{fo}$. To determine the latter, a fire growth rate α, fit for the scenario, has to be chosen from Table 24. Since the previous model lacks to specify the occupancy alpha is set to be a fast fire growth rate. This represents most occupancies while still being conservative. When alpha and $\dot{Q}_{fo}$ are known t_{fo} and the fire area a_f can be determined with Section 2.4. The resulting data is plotted in Figure 27. The smaller compartments from scenario four reach flashover more rapidly than the bigger ones from scenario three. The positive correlation between the floor area A_f and $\dot{Q}_{fo}$ is responsible for this, see Eq. (36).

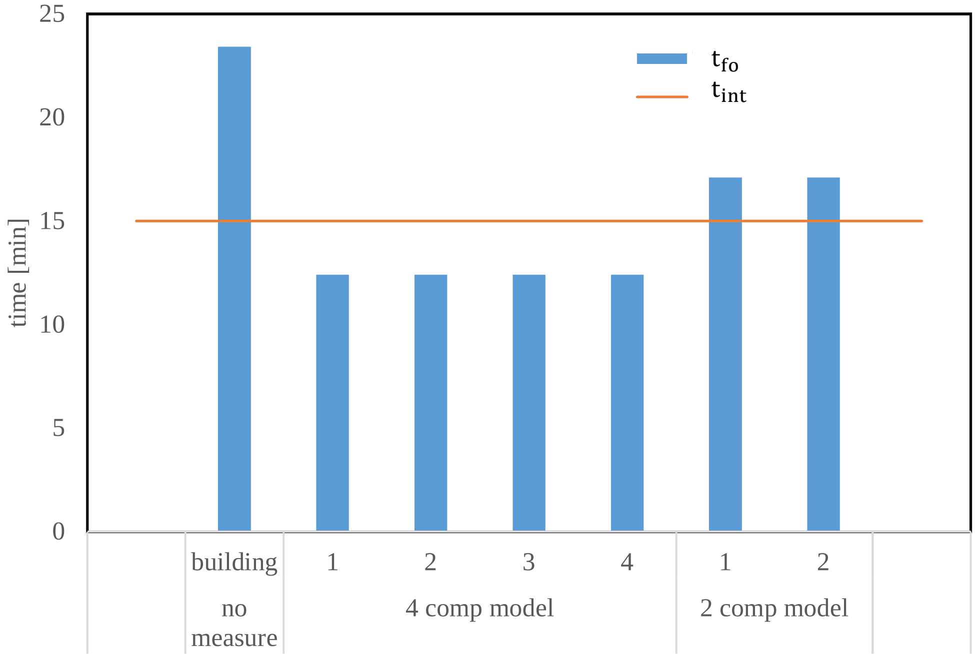

Figure 27: Comparing the time to FO and the intervention time of the fire brigade to determine if the fire area upon arrival of the fire

Based upon the previous P_{act} is calculated with the total floor area for scenario four and with the fire area a_f for scenario three. Figure 28 shows the respective areas together with cumulative distribution function of P_{act} as defined in Eq. (52).

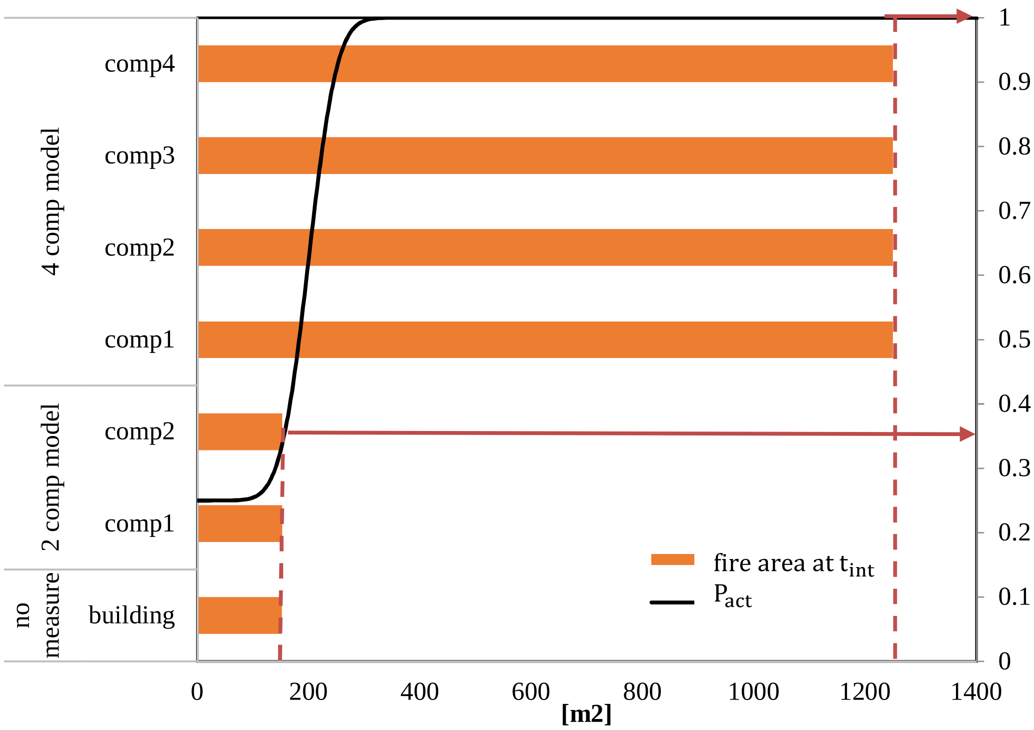

Figure 28: Determining the failure probability of the active suppression systems, detection and fire service, based upon the fire area at the intervention time of the fire brigade

The heat flux needed for FO and P_{fuel} are plotted in Figure 29. It's obvious that the floor areas for both scenarios accommodate more than enough fuel to reach flashover.

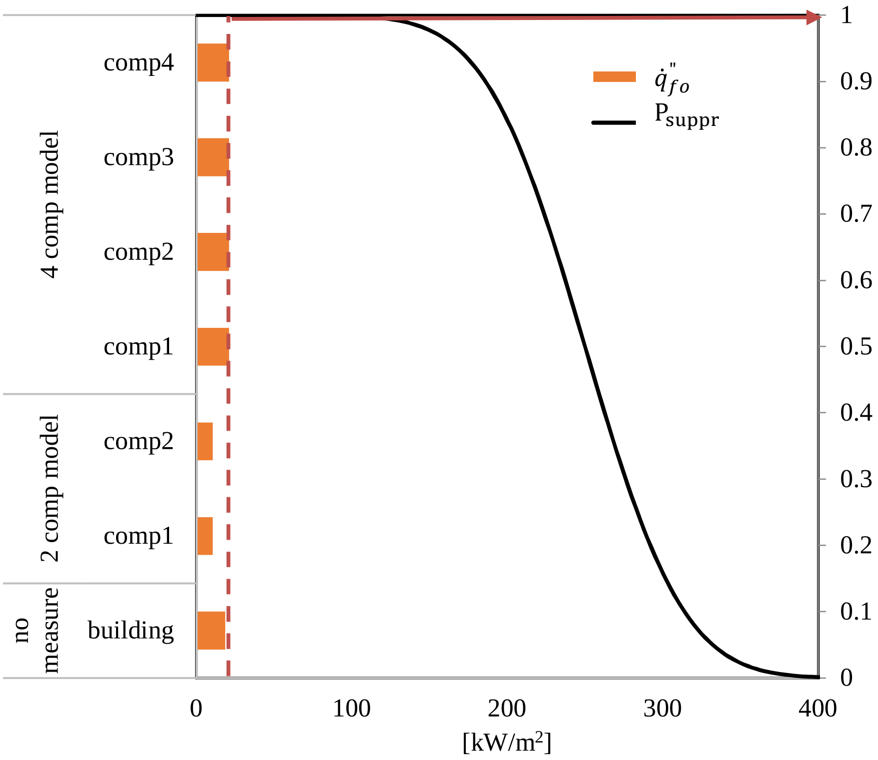

Figure 29: determining the probability that the peak fuel controlled HRR is bigger than the required HRR for FO based upon the total floor area, and thus fuel load, in each compartment

After P_{act} and P_{fuel} are established the resulting probability for FO can be calculated. A summary is given in Table 18.

Table 18: Values for the various probabilities of the new model

Variable	*Description*	*Both* P_{fw}	*New* $P_{poss,fo}$	P_{pass}	P_{suppr}	P_{fuel}	P_{spr}	$P_{fo,ign}$	*old* P_{fo}
1	No measure	/	1	1	0.34	1.00	/	0.34	0.2
2	Sprinkler	/	1	1	0.34	1.00	0.02	0.007	0.02
3	2 comp	$5*10^{-4}$	1	1	0.34	1.00	/	0.34	0.2
4	4 comp	$5*10^{-4}$	1	1	1.00	1.00	/	1	0.2

4.1.1.2. The minimum compartment size to allow for an effective fire service intervention

The HRR needed for FO, Section 2.1, in function of the width W, for a square floorplan, is shown in Figure 30. The curve is plotted for opening dimensions in the interval $0.1 < A_o\sqrt{H_o} < 20$. The bottom of the curve represents $A_o\sqrt{H_o} = 0.1$ and the upper boundary $A_o\sqrt{H_o} = 20$. Greater opening dimensions result thus in an upward translation of the curve, i.e., results in a less conservative minimum floor area, therefore only the bottom curve is considered, see further paragaphs.

The HRR upon arrival of the fire service is calculated and graphically represented for various fire growth rates, Section 2.1. The slow growth rate is excluded as it is not conservative.

The zone where the intervention happens before FO is represented by the area right of the intersection of the two curves, where $\dot{Q}_\alpha < \dot{Q}_{fo}$.

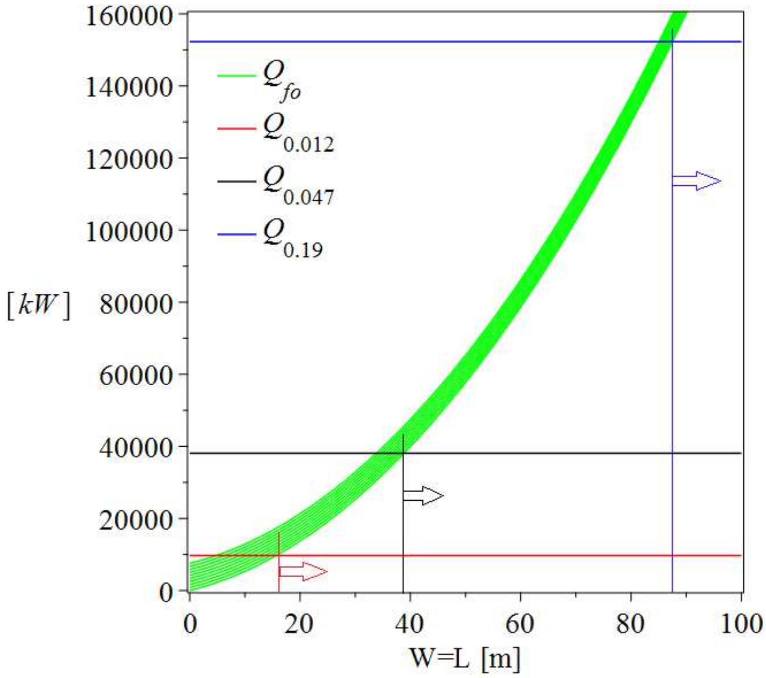

Figure 30: HRR needed for FO and the estimated HRR upon arrival of the fire service, intervention time of 15 min, for different fire growth rates [0.012,0.047,0.19]

The corresponding floor dimensions and failure probabilities, for a smoke detection system, are tabulated in Table 19. The medium and fast growth rate benefit respectively from a compartment size greater than 400 or 1600 m^2. The ultra-fast growth rate has an uncontrollable fire at t_{int} regardless if FO happened or not.

Table 19: Minimum area requirements for different fire growth rates in order to allow for timely intervention of the fire service

Growth rate	α *[kW/s^2]*	*≈ minimum floor area A_{min} [m^2]*	*Fire area at intervention if $A_F > A_{min}$ [m^2]*	*P_{suppr} in function of A_{min}*	*Resulting P_{act}*
Ultra fast	0.19	8100	609	1	1
Fast	0.047	1600	152	0.12	0.34
Medium	0.012	400	39	0	0.25

Applying F_Y in a strict sense would mean that a compartment size smaller than the predicted fire area would also be beneficial. The fire service arrives after FO but the total floor area involved is smaller than the fire area would be in a bigger pre-FO compartment. Whether this is beneficial depends on the total value of the ignition compartment compared to the adjacent compartment. The first will experience a total loss and P_{act} will only have a result on the fire spread. For the next discourse the assumptions is made that the value of the adjacent compartment is disproportionate big to the ignition compartment.

Figure 31 shows the effect of reducing the compartment size on P_{suppr} and P_{act}:

- Medium — P_{act} is already at its minimum and thus further reducing the compartment dimensions won't have any effect
- Fast — A reduction in P_{act} will only be witnessed in the interval $100 < A_f < 152$. P_{act} stays constant at 0.25 for $A_f < 100$
- Ultra-fast — A reduction in P_{act} will only be witnessed in the interval $100 < A_f < 300$. P_{act} stays constant at 0.25 for $A_f < 100$

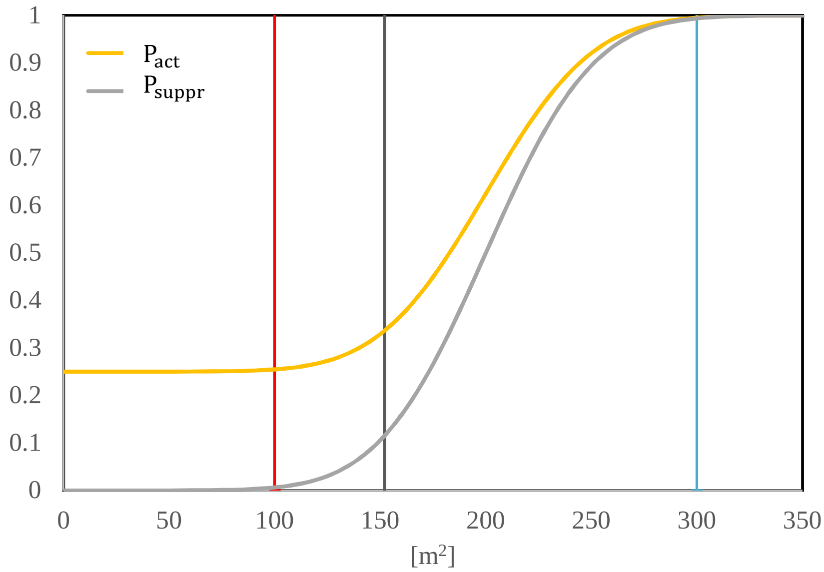

Figure 31: The effect of reducing the compartment size, to a value lower than the assumed fire area upon arrival of the fire service, on P_{act} and P_{suppr}

Further reducing the compartment size from 100 m^2 doesn't affect P_{act} but can result in a lower P_{fuel}. Figure 32 shows P_{fuel} and the heat flux needed for FO for various opening dimensions. The height is in function of the width of the assumed square floorplan, $H = 1.2 * W$. The reduction only occurs for small compartments with big openings and is thus not seen as a realistic scenario.

Nevertheless it shows that the effect of a reduced compartment size on P_{fuel} and P_{act} does not counteract each other.

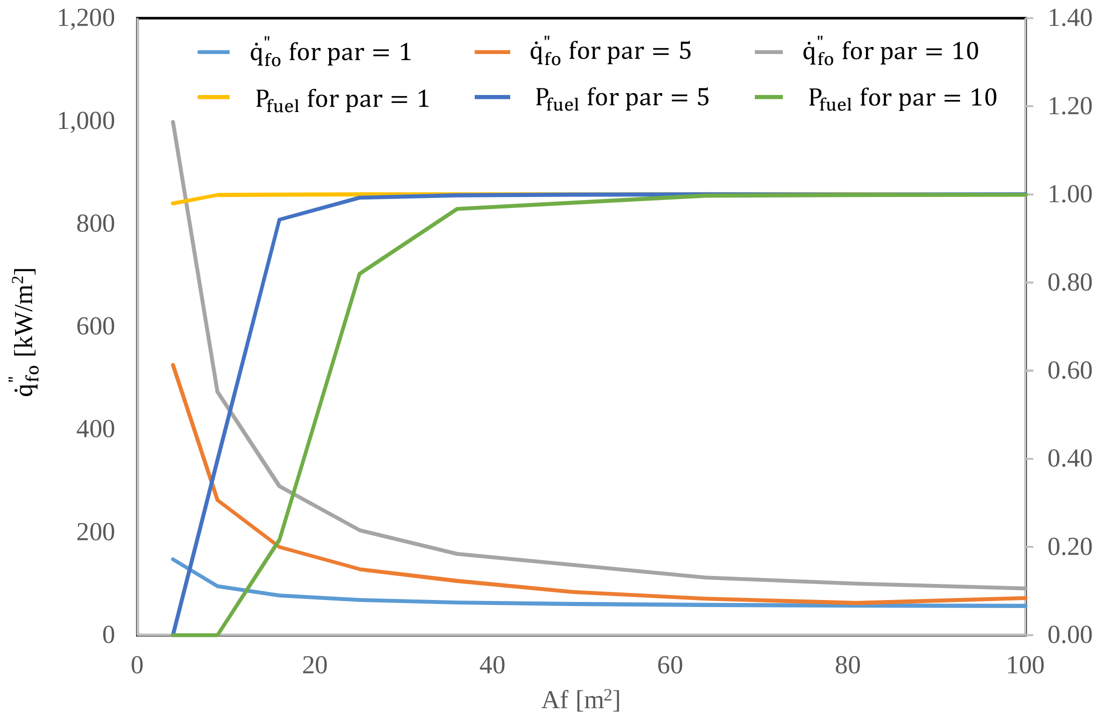

Figure 32: The effect of reducing the compartment size, height in function of the width of the assumed square floorplan, on P_{fuel} and q''_{fuel}

4.2. Influence of building size, compartment value and barrier material

In this example a methodology is put forward to assess the magnitude of compartment value needed for a positive CBA. The results will allow for an indication of the boundary conditions where compartmentation should be installed and where it has a significant benefit over sprinklers. Furthermore, by assessing the sensitivity of the fire wall failure probability a methodology is provided, which allows the private investor to decide whether an extra investment for a more redundant material is beneficial.

4.2.1. Input parameters

Building Research Establishment, BRE, conducted a research to assess the impact of the new 440,000 m^3 provision by DCLG [1], see Introduction. Their findings are summarized in the following.

- A common building height of 11.5 – 12 m is related to a usable free height of 11 m and a total floor area of approximately 40,000 m^2, which is the height of six stacked pallets or the maximum height a turret truck can reach.
- On average the Local Acts, prior to the provision, set the upper boundary at a volume of 7000m^3, assuming the same building height, this would mean a floor area of 580m^2. Hence, it is realistic to assume that warehouses have been built within those limits to avoid sprinkler installation. For this example 580 m^2 will be used as the lower boundary to represent a floor area that is workable in the warehouse sector.
- Even with the increase in occupancy analyses have shown that property protection greatly outweighs life safety. BRE estimates the total cost of injuries on £2.3m per year. Spread out over 30,000 warehouses this would sum up to £80 pounds per year per building. Considering fatalities has thus no noticeable effect on the CBA and shall be excluded from this example.
- The size distribution of warehouses for the period 1994 – 1998 in the UK and other European countries is shown in Table 52 and Table 53 of Appendix I. Based upon this data, and taking into account the minimum workable area for one compartment, various $A_{f,ext}$ in the range of 3,000 to 100,000 are chosen for this CBA, see Table 22. The interval represents approximately 23.2 per cent of the current stock.
- Analyzing data from 1966 and correcting for inflation to 2006 shows a value per unit floor area, i.e. the direct financial losses, of £210 $\pm$ £150.
- A payback period of 40 years is considered.
- A societal discount rate of 3.5 per cent is used in accordance with the Treasury Guidelines. As entrepreneurs expect a faster return of their investment a discount rate of 5 per cent is chosen for this example.
- A one-off installation cost of £32 per unit floor area for ESFR[4] sprinklers is tabulated and £45,000 for instalment of the water supplies. An annual maintenance of £750 - £1500 with

[4] New generation of sprinklers that have a 12 m depth range making instalment of sprinklers at various heights inside the racks unnecessary.

an average of £1125 is foreseen. The complete tables for sprinkler induced costs can be found in Appendix I.

- In a survey the price of compartmentalization was estimated by an interviewee as followed. A 100 m wide and 12 high compartmentalization wall would need at least three 5 m high fire doors to allow for passing of mechanized handling equipment. Furthermore, personnel escape doors have to be provided. The roof would need 2 m of extra fire protection material on both sides. The base of the firewall and the area around the doors needs impact protection. If the used material is assumed to be concrete blocks with an REI value of 160 the cost is estimated to be in the region of £185k to £205k. Per unit wall area this would be £154 to £170 with an average value of £162.

A summary of the study by BRE, together with other relevant parameters, is given Table 20. A storage building with full mail bags, plastic foam or stacked timber is chosen with a fast fire growth rate of 0.047 kW/s^2, see Table 25.

Table 20: Input parameters for a realistic warehouse example

parameter	*Indicator*	*unit*	*value*
H	Height	[m]	11
$s_{c,average}$	Average value per unit floor area	[euro/m^2]	240
L	Useful life	[yr]	40
γ	Continuous discount rate	[yr^{-1}]	0.05
$c_{0,spr}$	Installation cost sprinkler	[euro/$m^2_{\text{floor area}}$]	37
$c_{0,spr}$	Installation cost sprinkler water supplies	[euro]	51,000
M_{spr}	Maintenance cost sprinkler	[euro/yr]	1,300
$c_{0,comp}$	Installation cost fire wall for REI_{120}	[euro/$m^2_{\text{fire wall}}$]	180
$P_{fw,stone}$	Failure probability of a stone like compartmentation wall, higher than 9 m, with relevant penetrations	[-]	0.14
α	Fire growth rate	[kW/s^2]	0.047

The assumption is made that the various compartments for every scenario are equal in size, while pursuing a connectivity that resembles a realistic building, i.e., not overly long and narrow. The finite graph representations of the various building layouts can be found in Figure 37 of Appendix I, and allow for a visual interpretation of the scenarios.

4.2.2. Parameters that require a sensitivity analysis

An accurate approximation of the compartment value per unit floor area s_c is invaluable for a CBA. An increase in s_c will heighten the possible benefits and damage cost whereas the installation cost will stay constant (assuming that the proposed building layout doesn't change). As there is a big uncertainty in the value per unit floor area the example is repeated for the upper boundary $s_{c,upper}$ given by BRE. The first analysis will be denoted as CBA_{240} and the latter as CBA_{410}. In addition, the impact of the used material is researched by comparing the failure probability of a brick and metal stud barrier.

Table 21: The sensitivity of the compartment value and the failure probability of the barrier is researched in this example

parameter	*Indicator*	*unit*	*value*
$s_{c,upper}$	Upper limit of the value per unit floor area	[euro/m^2]	410
$P_{fw,metal}$	Failure probability of a metal stud like compartmentation wall, higher than 9 m, with relevant penetrations	[-]	0.34

4.2.3. First interpretation of the model output for the various scenarios

The various scenarios and results are shown in Table 22. Scenarios are denoted with two numbers, the first indicates the building floor area $A_{f,ext}$ and the second the number of compartments N.

Table 22: Different scenarios and the respective total net utility Z(p) and risk reduction ΔR for two different compartment values, 240 and 410 euro/m^2, respectively denoted CBA_{240} and CBA_{410}

scenario	*$A_{f,ext}$ [m^2]*	*N [-]*	*$A_{f,i}$ [m^2]*	***CBA_{240}*** *Z(p) [euro]*	*ΔR_1 [-]*	***CBA_{410}*** *Z(p) [euro]*	*ΔR_2 [-]*	*$\Delta R_1/\Delta R_2$ [-]*
1.spr	3,000	spr	3,000	-178,985	4,939	-175,486	8,438	1.71
1.6		6	500	-323,809	<u>1,539</u>	-322,719	2,629	1.71
1.4		4	750	-216,806	<u>92</u>	-216,741	157	1.71
1.2		2	1,500	-111,704	2,167	-110,169	3,702	1.71
2.spr	10,000	spr	10,000	-388,043	54,881	-349,168	93,755	1.71
2.9		9	1,111	-763,631	<u>28,369</u>	-743,536	48,464	1.71
2.6		6	1,667	-580,822	42,878	-550,451	73,249	1.71
2.4		4	2,500	-378,345	37,455	-351,814	63,986	1.71
2.2		2	5,000	-183,819	24,081	-166,762	41,138	1.71
3.spr	30,000	spr	30,000	-688,993	493,931	-339,124	843,800	1.71
3.9		9	3,333	-1,020,251	420,123	-722,664	717,710	1.71
3.6		6	5,000	-694,382	385,898	-421,038	659,242	1.71
3.4		4	7,500	-383,089	337,097	-144,312	575,874	1.71
3.2		2	15,000	-143,368	216,725	10,145	370,239	1.71

4.spr		spr	40,000	-674,824	878,100	-52,836	1,500,088	1.71
4.9		9	4,444	-916,315	746,885	-387,272	1,275,928	1.71
4.6	40,000	6	6,667	-561,359	686,041	-75,414	1,171,986	1.71
4.4		4	10,000	-232,316	599,284	192,177	1,023,777	1.71
4.2		2	20,000	-30,511	385,289	242,402	658,202	1.71
5.spr		spr	60,000	-317,198	1,975,726	1,082,274	3,375,198	1.71
5.9		9	6,667	-356,505	1,680,491	833,843	2,870,838	1.71
5.6	60,000	6	10,000	15,845	1,543,591	1,109,222	2,636,969	1.71
5.4		4	15,000	329,891	1,348,389	1,285,000	2,303,498	1.71
5.2		2	30,000	357,652	866,901	971,706	1,480,955	1.71
6.spr		spr	80,000	479,478	3,512,402	2,967,429	6,000,353	1.71
7.12		12	6,667	182,085	3,122,235			1.71
6.9	80,000	9	8,889	635,419	2,987,539	2,751,592	5,103,712	1.71
6.6		6	13,333	980,073	2,744,163	2,923,855	4,687,945	1.71
6.4		4	20,000	1,221,076	2,397,136	2,919,048	4,095,108	1.71
6.2		2	40,000	953,126	1,541,156	2,044,779	2,632,809	1.71
7.spr		spr	100,000	1,715,204	5,488,128	5,602,628	9,375,551	1.71
7.16		16	6,250	1,096,347	5,040,972			1.71
7.12		12	8,333	1,821,726	4,889,768			1.71
7.9	100,000	9	11,111	2,038,280	4,668,030	5,344,801	7,974,551	1.71
7.6		6	16,667	2,315,442	4,287,754	5,352,601	7,324,913	1.71
7.4		4	25,000	2,430,650	3,745,525	5,083,730	6,398,606	1.71
7.2		2	50,000	1,750,619	2,408,057	3,456,326	4,113,764	1.71

The minimum compartment floor area A_{min}, allowing an effective fire service intervention, was determined in Section 4.1.1.2, and found to be ≈1600 m^2 for a fast fire growth rate. Once A_{min} is reached, a further increase of N results in an augmentation of the risk. The effect explains the decrease in risk reduction ΔR for scenarios 2.9, 1.4 and 1.6 (relative to respectively scenario 2.6 and 1.2).

CBA_{240} shows a positive total net utility $Z(p)$ for scenarios five, six and seven, for CBA_{410} scenario four is also beneficial. The $Z(p)$ values marked in green indicate the number of compartments that maximize the return, for a given $A_{f,ext}$. The results are in line with Eq. (13) of Section 1.3.3. The derivative from the total net utility returns the maximum, or minimum, value when one optimization parameter is assessed. A private investor with a risk-adverse attitude can decide not to comply with the ideal number of compartments. As long as $A_{f,i}$ is bigger than A_{min}

an increase in N will propagate a decrease of risk. It should be noted that an amount of compartments that results in a negative CBA should be avoided.

The scenarios that are not cost-beneficial in CBA_{240}, but are in CBA_{410} demonstrate that there is a minimum value per unit floor area for compartmentation $s_{c,min,comp}$ and sprinkler $s_{c,min,spr}$ to return a positive $Z(p)$. The last column in Table 22 indicates that the increment in risk reduction is equal to the ratio of $s_{c,upper}$ to $s_{c,average}$. Because the compartment value is uniformly distributed a linear relationship between s_c and the damage cost and the maximum possible benefits exists, see Eq. (64) and (66). The implementation cost is independent of s_c and is thus a constant for both situations. The mathematical representation of the above is given by Eq. (68).

$$Z(p)_{upper} = \frac{s_{c,upper}}{s_{c,average}} \Delta R_{average} - C(p) \tag{68}$$

Interpreting $s_{c,upper}$ as $s_{c,min}$ and equating Eq. (68) to zero leads to Eq. (69). The only unknown is $s_{c,min}$ and the equality can be solved.

$$s_{c,min} = \frac{C(p)}{\Delta R_{average}} * s_{c,average} \tag{69}$$

The gray values in Table 22 demonstrated that for a higher compartment value per unit floor area sprinkler installation becomes more beneficial, denoted $s_{c,spr}$. The tipping point is obtained following a similar methodology as for Eq. (82):

$$\begin{gathered} \frac{s_{c,spr}}{s_{c,average}} \Delta R_{comp} - C(p)_{comp} = \frac{s_{c,spr}}{s_{c,average}} \Delta R_{spr} - C(p)_{spr} \\ \Leftrightarrow s_{c,spr} = \left(\frac{C(p)_{comp} - C(p)_{spr}}{\Delta R_{comp} - \Delta R_{spr}} \right) s_{c,average} \end{gathered} \tag{70}$$

When the installation cost of compartmentation is greater, and the respective risk reduction lower than sprinklers, Eq. (70) returns a negative value. For these scenarios sprinkler implementation is always more beneficial regardless of s_c.

The results for $s_{c,min}$ and $s_{c,spr}$ are graphically analyzed in Section 4.2.4 and 4.2.5. The calculation and absolute values for all scenarios can be found in Table 55 of Appendix I.

4.2.4. The minimum compartment floor area needed for compartmentation and sprinkler to be beneficial

Figure 33 shows $s_{c,min}$ in function of $A_{f,ext}$ and N. The scenarios with a compartment size less than 1600 m^2, see Table 19, are excluded as the respective $s_{c,min}$ is not comparable due to the shortening of t_{fo}. The lines follow a rather smooth curve from 30,000 to 100,000 m^2 requiring a $s_{c,min}$ between 823 and 66 and euro/m^2. Projects smaller than 30,000 m^2 require an exponential growth in compartment value, $s_{c,min} > 2000$ euro/m^2. Hence, the conclusion is made that the benefit of compartmentation is exploited to its full potential in the range $A_{f,ext} > 30{,}000$.

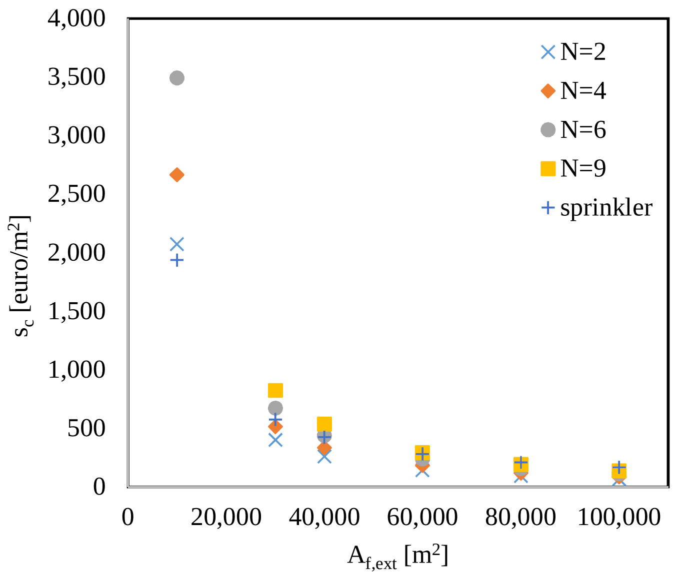

Figure 33: The minimum value per unit floor area needed for a positive CBA in function of the building floor area $A_{f,ext}$ and the number of compartments N

4.2.5. When to install sprinkler, compartmentation, or other measures for different characteristics of the private investor

Figure 34 and Figure 35 show the values for $s_{c,min}$, in function of the number of compartments, for $A_{f,ext} = 100{,}000$ m^2 and $A_{f,ext} = 30{,}000$ m^2.

The following areas can be defined:

- A When s_c is smaller than $s_{c,min,spr}$ and $s_{c,min,comp}$ both risk measures return a negative CBA and other mitigation measures should be researched
- B When the goal is to maximizes Z(p), compartmentation should be pursued for the interval $s_{c,min,comp} \leq s_c < s_{c,spr}$
- C When the goals is to maximize Z(p), sprinkler installation is the optimum choice for the interval $s_c \geq s_{c,spr}$
- D When the goals is to maximize ΔR, while having a positive CBA, sprinkler installation should be pursued when $s_c > s_{c,min,sprinklers}$
- E Once $s_{c,min,spr} < s_{c,min,comp}$ sprinklers will result in the maximum Z(p) and ΔR, i.e., sprinklers should be implemented

The graphical representations for other building sizes and the absolute values for all the scenarios can be found in Appendix I.

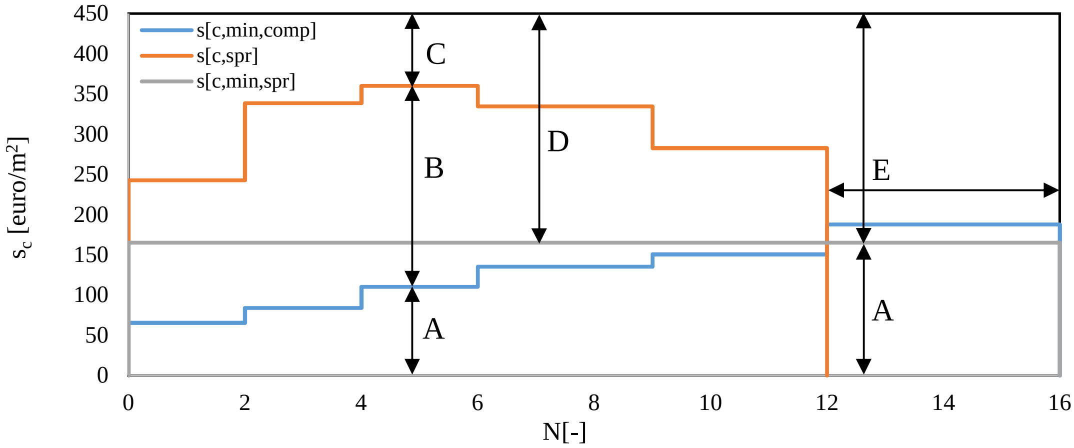

Figure 34: Minimum compartment value per unit floor area needed to make sprinkler and compartmentation installation viable in function of the number of compartments N and for a building floor area $A_{f,ext}$ of 100,000 m^2. [A] indicates the area where both compartmentation and sprinkler are not beneficial, [B] indicates the area where compartmentation returns a greater net utility Z(p) than sprinkler, [C] indicates the area where sprinkler returns the greatest Z(p) and [E] indicates the area where sprinkler return the greatest Z(p) AND risk reduction ΔR

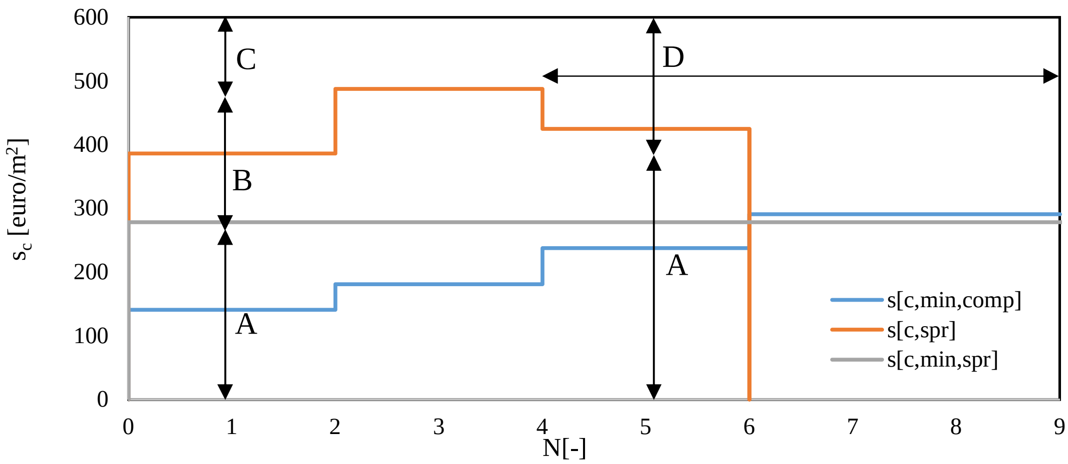

Figure 35: Minimum compartment value per unit floor area needed to make sprinkler and compartmentation installation viable in function of the number of compartments N and for a building floor area $A_{f,ext}$ of 30,000 m^2. [A] indicates the area where both compartmentation and sprinkler are not beneficial, [B] indicates the area where compartmentation returns a greater net utility Z(p) than sprinkler, [C] indicates the area where sprinkler returns the greatest Z(p) and [E] indicates the area where sprinkler return the greatest Z(p) AND risk reduction ΔR

4.2.6. The impact of the used barrier material on the CBA

Scenario 7 and 6 are repeated with $P_{fw,metal} = 0.34$ to assess the impact of the barrier material. In reality this example can be translated to a private investor who has to decide whether it is beneficial to make an extra investment for a more redundant material, as it is reasonable to assume that a lower P_{fw} involves a higher implementation cost (e.g., more raw material needed, more costly materials). The case with $P_{fw,metal}$ will be seen as the reference scenario.

The assumption is made that the contractor has the necessary skill to implement the barrier according to the required standard, which makes the difference in failure probability solely material dependent. The results of the simulation can be found in Table 23.

A reduction in P_{fw} results in a lower damage cost for every scenario, as can be seen from the negative values for the extra risk reduction $\Delta D = D(p)_{0.14} - D(p)_{0.34}$. The layouts with more compartments experience the biggest ΔD, as fire spread through multiple compartments will experience an exponential reduction. For example, a loss due to a fire spread through three compartments will be reduced with a factor $0.34^2/0.14^2 \approx 5.9$ for the reference situation on installation of the better material, whereas for a two compartment model, i.e., failure of maximum one barrier, this is $0.34^1/0.14^1 \approx 2.4$. In addition, more compartments results in more possible scenarios for which the reduction can take place.

Table 23 demonstrates that the percentage extra risk reduction $\Delta D/D(p)_{0.34}$ is independent of the building or compartment floor area, as the number of fire wall failures is the chief variable. It was calculated that the measure induces an extra risk reduction of 15 and 42 per cent for respectively $N = 2$ and $N = 6$.

The greater risk reduction for layouts with more compartments is counteracted by a greater implementation cost, as more compartments inherently signify a greater barrier volume that has to be upgraded. To determine the beneficiality of the investment, $\Delta C_{poss} = [\Delta D/D(p)_{0.34}]/C(p)$ is calculated to represent the maximum extra investment before $Z(p)_{0.14} < Z(p)_{0.34}$. Table 23 shows that for scenario seven the extra investment can be 146 or 81 per cent for respectively $N = 2$ and $N = 6$.

Table 23: Analyzing the effect of the used barrier material by comparing the failure probabilities of a metal-stud and brick wall for scenario seven and six (respectively a building floor area of 100,000 m^2 and 80,000 m^2)

			CBA$_{410}$			
scenario	7.6	7.4	7.2	6.6	6.4	6.2
N [-]	6	4	2	6	4	2
A_f [m^2]	16,667	25,000	50,000	13,333	20,000	40,000
B(p) [euro]	9,566,889	9,566,889	9,566,889	6,122,809	6,122,809	6,122,809
C(p) [euro]	1,972,313	1,314,875	657,438	1,764,090	1,176,060	588,030
			$P_{fw,metal}$=0.34			
$D(p)_{0.34}$ [euro]	3,837,319	4,759,062	6,409,813	2,455,884	3,045,799	4,102,280
$Z(p)_{0.34}$ [euro]	3,757,257	3,492,952	2,499,639	1,902,835	1,900,950	1,432,499
			$P_{fw,brick}$=0.14			
$D(p)_{0.14}$ [euro]	2,241,976	3,168,284	5,453,125	1,434,864	2,027,702	3,490,000
$Z(p)_{0.14}$ [euro]	5,352,601	5,083,730	3,456,326	2,923,855	2,919,048	2,044,779
			analysis			
ΔD [euro]	-1,595,343	-1,590,778	-956,687	-1,021,020	-1,018,098	-612,280
$\Delta D/D(p)_{0.34}$ [-]	-0.42	-0.33	-0.15	-0.42	-0.33	-0.15
ΔC_{poss} [-]	0.81	1.21	1.46	0.58	0.87	1.04

The building Cost Information Service in the UK, BCIS, performed a cost breakdown for partitions, walls and ceilings, of which a part can be freely accessed on the website of "The Architects' Journal" [37]. The cost for a 125 mm stud partition wall, without acoustic isolation and with fireproof plasterboard, was estimated to be 120 euro/m^2, which would mean an extra investment ΔC of 50 per cent relative to the predetermined cost of a concrete partition. Based upon this data, the private investor should decide to implement the extra safety measure as $\Delta C < \Delta C_{poss}$.

4.3. Summary of results

The comparison with the previous model allowed to assess the impact of the compartment size on the probability of FO, which resulted in minimum floor areas for various fire growth rates.

The second example established the compartment value as a paramount parameter, due to the discrepancy in the literature the required magnitude for a positive CBA was assessed, rather than assigning an absolute value. Graphs were constructed to indicate the area where compartmentation, sprinkler or none were beneficial.

Lastly, a methodology was set up to assess whether an investment in a more redundant barrier material is beneficial

Chapter 5

Conclusion

5.1. Conclusion

The scope of the thesis was to propagate a tool with respect to compartmentation that can be used by the private investor to assess whether a safety investment is beneficial, while at the same time giving an awareness of the expected possible profit not utilised. The basis of the construct is that of a Cost-Benefit Analysis in conjunction with a probabilistic risk assessment, this immediately identified the key problem as determining the respective damage cost, due to its dependency on the fire spread path.

It was demonstrated how the adjacency matrix can be used to define the connectivity between compartments and for various building layouts, after which the characteristics proofed invaluable to derive equations for the construct of a mathematical model that derives all failure scenarios. In parallel, an assessment of the chief failure event flashover was made, as an accurate approximation was essential to determine the *expected* consequences of the scenarios. To establish its probability of occurrence, the stages leading to the onset of FO were first determined and then quantified in a probabilistic risk assessment, this allowed to explicitly demonstrate the benefit of compartmentation. The hands on approach followed for the methodology avoided the use of complicated mathematical real fire models or computational zone models, in order to design a tool that is comprehendible for both experts and non-experts.

Results showed that significant reduction of compartment size can have an adverse effect on risk, in order to avoid the unfavourable conditions calculations were done to provide the user with a minimum compartment size. The magnitude ranged from 400 to 8100 m^2 for various fire growth rates. Also, it was established that the safety measure is only economically justifiable for large buildings, as simulations indicated that an exponential growth of compartment value is needed for building floor areas smaller than 30,000 m^2. Due to the paramount necessity for an accurate estimation of the average value per unit floor area and the discrepancy in the literature, a study was undertaken to assess the required magnitude that is needed for a positive CBA, rather than establishing an absolute value. The results are graphically represented in this thesis for various building sizes, allowing the entrepreneur to assess whether compartmentation, or sprinkler installation, is viable for his or her company.

The work presented provides an approach that can be used by laypeople and private investors alike to understand, calculate and mitigate their exposure to fire risk, with this knowledge they can counteract insurance companies and others alike that today control the debate on how to deal with risk.

5.2. Future work

A study of the CBA with the use of the parametric fire curves, i.e., realistic fire model, or a computational zone model would allow to assess the assumptions and simplifications made for the probabilistic risk assessment of flashover. In conjunction an attempt could be made to include the calculation of the thermal resistance and exposure of a solid element, as results showed that the failure probability of the barrier has a considerable impact on the result of the CBA.

The thesis is mainly written from an engineering point of view and an equivalent thorough study to incorporate other economic aspects is needed for a tool that has strong fundaments in both disciplines.

A user friendly interface should be constructed to make the model accessible for everyone.

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Appendix A

Previous model risk equation derivation for a four compartment building layout

An attempt is made here to trace back the steps that preceded Eq. (26), in order to get a better understanding of the limitations of the previous model

There will be four different scenarios as a fire can start in compartment one, two, three or four. Following the same logic as in section 1.6.1 and 1.6.2 a model is reconstructed to verify the validity of Eq. (25). The starting point for the derivations below is that of a fire starting in compartment 1.

The probability for FO in compartment one is given by Eq. (71).

$$P_{4,FO,1} = P_{fo} * \left(0.25 * P_f * B * L\right) \tag{71}$$

The expected damage in case of FO in compartment one is given by Eq. (72). Since the four compartments are equal in size the value is constant.

$$S_{4,FO} = 0.25 * S * B * L \tag{72}$$

The probabilities that FO occurs in one of the two nearest adjacent compartments is given by Eq. (73) and Eq. (74).

$$P_{4,FO,2} = P_{4,FO,1} * \left[P_{fw} * H * \frac{B}{2}\right] * P_{fo} \tag{73}$$

$$P_{4,FO,3} = P_{4,FO,1} * \left[P_{fw} * H * \frac{L}{2}\right] * P_{fo} \tag{74}$$

FO conditions in compartment two or three can cause fire spread and thus FO to compartment four. Because one of these events is enough to cause FO the summation, rather than the multiplication, of the probabilities is taken.

$$P_{4,FO,4} = P_{4,FO,2} * \left[P_{fw} * H * \frac{L}{2}\right] * P_{fo} + P_{4,FO,3} * \left[P_{fw} * H * \frac{B}{2}\right] * P_{fo} \tag{75}$$

The total risk of a fire that started in compartment one is given by Eq.

$$R_{scenario\ 4} = S_{4,FO}(P_{4,FO,1} + P_{4,FO,2} + P_{4,FO,3} + P_{4,FO4}) \tag{76}$$

Because the fire can start in compartment one, two, three or four the total risk is the summation of all, identical, scenarios as shown in in Eq. (77).

$$R_4 = 4\left[S_{4,FO}(P_{4,FO,1} + P_{4,FO,2} + P_{4,FO,3} + P_{4,FO4})\right] \tag{77}$$

The latter is expanded into Eq. (78) and Eq. (26) is repeated so a comparison can be made.

$$R_4 = 0.25 * R_1 * \left[1 + P_{fo}P_{fw}H\left(\frac{B}{2} + \frac{L}{2}\right) + 0.5 * B * L * P_{fo}^2 * P_{fw}^2 * H^2\right] \tag{78}$$

$$R_4 = 0.25 * R_1\left[1 + P_{fo}P_{fw}H\left(\frac{B}{2} + \frac{L}{2}\right) + \left(P_{fo}P_{fw}\right)^2 H\left(\frac{B}{2} + \frac{L}{2}\right)\right] \tag{79}$$

As can be seen the terms in red, concerning the FO probability of compartment four, are different. $T_1 = 0.25 * R_1 * 0.5 * B * L * P_{fo}^2 * P_{fw}^2 * H^2$ and $T_2 = 0.25 * R_1 * \left(P_{fo}P_{fw}\right)^2 H\left(\frac{B}{2} + \frac{L}{2}\right)$ are expanded in respectively Eq. (81) and Eq. (80) to see where the difference comes from.

$$T_1 = 0.25SBL * \left[(0.25P_f P_{fo}BL) * \left(P_{fw}H\frac{B}{2}\right) * P_{fo} * \left(P_{fw}H\frac{L}{2}\right) * P_{fo} + (0.25P_f P_{fo}BL) * \left(P_{fw}H\frac{L}{2}\right) * P_{fo} * \left(P_{fw}H\frac{B}{2}\right) * P_{fo}\right] \tag{80}$$

$$T_2 = 0.25SBL * \left[\left(0.25P_f P_{fo} BL\right) * \left(P_{fw} H \frac{B}{2}\right) * P_{fo} * P_{fw} * P_{fo} + \left(0.25P_f P_{fo} BL\right) * \left(P_{fw} H \frac{L}{2}\right) * P_{fo} * P_{fw} * P_{fo} \right] \quad (81)$$

The discrepancy is caused due the fact that the previous example for the second fire spread, from compartment two to four and from three to four, didn't multiply the failure probability per m^2 of the fire wall, P_{fw}, with the surface area.

Appendix B

Tables to determine the fire growth coefficient

Table 24: Typical growth rates recommended for various types of occupancies. Reconstructed from [18], [27]

Type of occupancy	*Growth rate α*
Dwelling, schools, offices	Medium → fast
Hotels, nursing homes, etc.	Fast
Shopping centres, entertainment centres	Fast → Ultra-fast
Hazardous industries	Not specified

Table 25: Typical growth rates recommended for various types of occupancies. Reconstructed from [38]

Type of occupancy	*Growth rate α*
Densely packed wood products, Art-gallery, Public space for transport means, **Storage building with few combustible materials**	slow
Solid wooden furniture items with small amounts of plastic, Dwelling, Hospital bedroom, Hotel bedroom, Hotel reception, Office buildings, School classroom, **Storage building for cotton or pyester sprung mattresses**	medium
High stacked wood pallets, Shopping centre, Library, Theatre, Cinema, Cartons on pallets, Some upholstered furniture, **Storage buildings with full mailbags, plastic foam or stacked timber**	fast
Upholstered furniture, High stacked plastic materials, Thin wood furniture such as wardrobes, Chemical plant, **Storage buildings with alcoholic liquids or upholstered furniture**	Ultra-Fast

Appendix C

Examples of other fire induced indirect costs

Table 26: Example of direct and indirect cost attributes, reproduced from [35]

legal	*Damage*	*Human and environmental*
Fines	Damage to own material/property	Compensation victims
Interim lawyers	Damage to other companies material/property	Injured employees
Specialized lawyers/ Experts at hearings	Damage to public material/property	Recruitment
Internal research team	Damage to surrounding living areas	Environmental damage
Medical	*Supply-chain*	*Personnel*
Medical treatment at location	Production-related	Productivity of personnel
Medical treatment in hospitals and revalidation	Start- up	Training of new or temporary employees
Using medical equipment and devices	Schedule-related	Wages
Medical transport		

Insurance	*Intervention*	*Reputation*
Insurance premium	Fire service intervention	Share price
	On-site intervention	Accident investigation

Appendix D

Tables with the failure probabilities of fire walls

Table 27: Failure probability of a brick compartmentalization wall with a height lower than 9 m and with NO relevant penetrations. Reconstructed from [2]

	REI [min]						
Equivalent fire duration [min]	*0*	*30*	*60*	*120*	*240*	*360*	*480*
30	1	**0.05**	0.03	0.02	0.01	0.01	0.01
60	1	0.43	**0.05**	0.03	0.02	0.01	0.01
120	1	0.92	0.43	**0.05**	0.03	0.02	0.01
240	1	1	0.92	0.43	**0.05**	0.03	0.02
360	1	1	1	0.92	0.43	**0.05**	0.03
480	1	1	1	1	0.92	0.43	**0.05**

Table 28: Failure probability of a brick compartmentalization wall with a height lower than 9 m and with relevant penetrations. Reconstructed from [2]

	REI [min]						
Equivalent fire duration [min]	*0*	*30*	*60*	*120*	*240*	*360*	*480*
30	1	**0.07**	0.07	0.07	0.07	0.0	0.07
60	1	0.62	**0.07**	0.07	0.07	0.07	0.07
120	1	0.98	0.62	**0.07**	0.07	0.07	0.07
240	1	1	0.98	0.62	**0.07**	0.07	0.07
360	1	1	1	0.98	0.62	**0.07**	0.07
480	1	1	1	1	0.98	0.62	**0.07**

Table 29: Failure probability of a brick compartmentalization wall with a height higher than 9 m and with NO relevant penetrations. Reconstructed from [2]

	REI [min]						
Equivalent fire duration [min]	*0*	*30*	*60*	*120*	*240*	*360*	*480*
30	1	**0.12**	0.06	0.04	0.03	0.2	0.01
60	1	0.74	**0.10**	0.06	0.04	0.03	0.02
120	1	0.98	0.74	**0.10**	0.06	0.04	0.03
240	1	1	0.98	0.74	**0.10**	0.06	0.04
360	1	1	1	0.98	0.74	**0.10**	0.06
480	1	1	1	1	0.98	0.74	**0.10**

Table 30: Failure probability of a brick compartmentalization wall with a height higher than 9 m and with relevant penetrations. Reconstructed from [2]

	REI [min]						
Equivalent fire duration [min]	*0*	*30*	*60*	*120*	*240*	*360*	*480*
30	1	**0.14**	0.14	0.14	0.14	0.14	0.14
60	1	0.87	**0.14**	0.14	0.04	0.14	0.14
120	1	1	0.87	**0.14**	0.14	0.14	0.14
240	1	1	1	0.87	**0.14**	0.14	0.14
360	1	1	1	1	0.87	**0.14**	0.14
480	1	1	1	1	1	0.87	**0.14**

Table 31: Failure probability of a metal stud wall with a height lower than 9 m and with NO relevant penetrations. Reconstructed from [2]

	REI [min]						
Equivalent fire duration [min]	*0*	*30*	*60*	*120*	*240*	*360*	*480*
30	1	**0.09**	0.06	0.04	0.03	0.02	0.01
60	1	0.43	**0.09**	0.06	0.04	0.03	0.02
120	1	0.96	0.43	**0.09**	0.06	0.04	0.03
240	1	1	0.96	0.43	**0.09**	0.06	0.04
360	1	1	1	0.96	0.43	**0.09**	0.06
480	1	1	1	1	0.96	0.43	**0.09**

Table 32: Failure probability of a metal stud wall with a height lower than 9 m and with relevant penetrations. Reconstructed from [2]

	REI [min]						
Equivalent fire duration [min]	*0*	*30*	*60*	*120*	*240*	*360*	*480*
30	1	**0.11**	0.11	0.11	0.11	0.11	0.11
60	1	0.62	**0.11**	0.11	0.11	0.11	0.11
120	1	0.99	0.62	**0.11**	0.11	0.11	0.11
240	1	1	0.99	0.62	**0.11**	0.11	0.11
360	1	1	1	0.99	0.62	**0.11**	0.11
480	1	1	1	1	0.99	0.62	**0.11**

Table 33: Failure probability of a metal stud wall with a height higher than 9 m and with NO relevant penetrations. Reconstructed from [2]

	REI [min]						
Equivalent fire duration [min]	*0*	*30*	*60*	*120*	*240*	*360*	*480*
30	1	**0.31**	0.20	0.14	0.09	0.06	0.04
60	1	0.74	**0.31**	0.20	0.14	0.09	0.06
120	1	0.99	0.74	**0.31**	0.20	0.14	0.09
240	1	1	0.99	0.74	**0.31**	0.20	0.14
360	1	1	1	0.99	0.74	**0.31**	0.20
480	1	1	1	1	0.99	0.74	**0.31**

Table 34: Failure probability of a metal stud wall with a height higher than 9 m and with relevant penetrations. Reconstructed from [2]

	REI [min]						
Equivalent fire duration [min]	*0*	*30*	*60*	*120*	*240*	*360*	*480*
30	1	**0.34**	0.34	0.34	0.34	0.34	0.34
60	1	0.87	**0.34**	0.34	0.34	0.34	0.34
120	1	1	0.87	**0.34**	0.34	0.34	0.34
240	1	1	1	0.87	**0.34**	0.34	0.34
360	1	1	1	1	0.87	**0.34**	0.34
480	1	1	1	1	1	0.87	**0.34**

Appendix E

The equivalent time of fire exposure

The equivalent time of fire exposure $t_{e,d}$, mathematically represented by Eq. (82), is used to relate the performance of structural elements, tested with the standard fire curve, to the actual boundary conditions of the compartment. The methodology, as explained in BS EN1991-1-2:2002 [29], is elaborated in this section.

$$t_{e,d} = (q_{f,d} k_b w_f) k_c \ [min] \tag{82}$$

Where:

- $q_{f,d}$ is the design fire load density [MJ/m^2], see Eq. (84)
- k_b is the conversion factor [min.m^2/MJ], see Table 38
- w_f is the ventilation factor [-], see Eq. (85) and Eq. (86)
- k_c is the correction factor function of the material composing structural cross-sections [-], see Table 39

For the structural element not to fail $t_{e,d}$ should be smaller than the design value of the standard fire resistance of the members $t_{fi,d}$ and thus the acceptance criteria is given by:

$$t_{e,d} < t_{fi,d} \tag{83}$$

The design fire load density $q_{f,d}$ in Eq. (82) is calculated as followed:

$$q_{f,d} = q_{f,k} m \delta_{q1} \delta_{q2} \delta_n \ [MJ/m^2] \ with \ \delta_n = \prod_{i=1}^{10} \delta_{ni} \tag{84}$$

Table 35: Characteristic fire load densities [MJ/m^2] for different occupancies. Reconstructed from [29]

Occupancy	Average	80th Percentile
Dwelling	780	948
Hospital (room)	230	280
Hotel (room)	310	377
Library	1500	1824
Office	420	511
Classroom of a school	285	347
Shopping centre	600	730
Theatre (cinema)	300	365
Transport (public space)	100	122
NOTE Gumbel distribution is assumed for the 80th percentile		

Table 36 shows the values for δ_{q1} and δ_{q2}. However, the norm fails to specify the intervals. For this thesis the floor areas are taken as the mean value.

Table 36: Factors δ_{q1} and δ_{q2} to determine the chance of ignition based upon the floor area and occupancy. Reconstructed from [29]

Compartment floor area A_f [m^2]	*Danger of fire activation δ_{q1}*	*Examples of occupancies*	*Danger of fire activation δ_{q2}*
25	1.1	Art gallery, museum, swimming pool	0.78
250	1.50	Offices, residence, hotel, paper industry	1.00
2,500	1.90	Manufactory for machinery & engines	1.22
5,000	2.00	Chemical laboratory, painting workshop	1.44
10,000	2.13	Manufactory of fireworks or paints	1.66

Table 37: Factors δ_{ni} in function of active firefighting measures. Reconstructed from [29]

Automatic fire suppression				*Automatic fire detection*			*Manual fire suppression*				
Automatic water extinguishing system	*Independent water supplies*			*Automatic fire detection & alarm*		*Automatic alarm transmission to fire brigade*	*Work fire brigade*	*Off site fire brigade*	*Safe access routes*	*Fire fighting devices*	*Smoke exhaust system*
δ_{n1}	δ_{n2}			δ_{n3}	δ_{n4}	δ_{n5}	δ_{n6} or δ_{n7}		δ_{n8}	δ_{n9}	δ_{n10}
	#0	#1	#2	By heat	By smoke						
0.61	1.0	0.87	0.7	0.87	0.73	0.87	0.61	0.78	0.9 or 1 or 1.5	1.0 or 1.5	1.0 or 1.5

The conversion factor k_b can be related to the thermal properties $b = \sqrt{\rho c \lambda}$ as shown in Table 38. If the properties are not available $k_b = 0.07$ is taken. When considering a boundary with different layers of material b can be determining as described in BS EN 1991-1-2:2002 [7, pp. 30-32]. In this thesis it is assumed that the compartment's. 4 walls, roof and floor, are made of the same material.

Table 38: Conversion factor k_b depending on the thermal properties of the enclosure [29]

$b = \sqrt{\rho c \lambda}$ [J/m²s^(1/2)K]	k_b [min*m²/MJ]
$b > 2{,}500$	0.04
$720 \leq b \leq 2{,}500$	0.055
$b < 720$	0.07

For compartments with a floor area A_f larger than 100 m^2 the ventilation factor w_f can be calculated as followed [29]:

$$w_f = \left(\frac{6.0}{H}\right)^{0.3}\left(0.62 + \frac{90(0.4-\alpha_v)^4}{1+b_v\alpha_h}\right) \geq 0.5\ with: \tag{85}$$

$$0.025 \leq \alpha_v = \frac{A_v}{A_f} \leq 0.25\ ;\ \alpha_h = \frac{A_h}{A_f}; b_v = 12.5(1 + 10\alpha_v - \alpha_v^2) \geq 10.0$$

It should be noted that the code fails to specify what to do if the ventilation factor falls outside of the prescribed boundaries.

If $A_f < 100\ m^2$ and $A_h = 0$ Eq. (85) can be reduced to:

$$w_f = \frac{O^{-\frac{1}{2}}A_f}{A_t}\ with: \qquad 0.02 \leq O = \frac{A_v\sqrt{h_{eq}}}{A_t} \leq 0.20 \tag{86}$$

The correction factor for various materials is given in Table 39.

Table 39: Correction factor k_c in order to cover various materials [29]

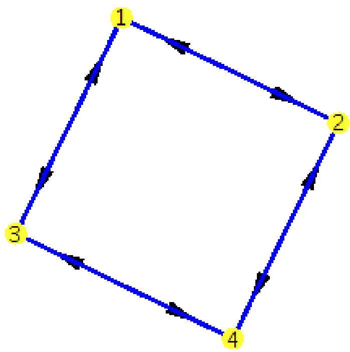
Cross-section material	*Correction factor k_c*
Reinforced concrete	1.0
Protected steel	1.0
Not protected steel	13.7*O

Appendix F

Example of the model output for the annual failure probability with a four compartment building layout

Equations (56) to (60) were programmed in the mathematical software Maple together with the parameters N, n_0 and AM for a specific building layout. The output, i.e. the possible fire spread scenarios and their annual loss probability, are shown in Table 40. For the building layout it was calculated that: for compartment one and two the fire service can intervene before FO, for compartment three and four after FO.

Table 40: All fire spread scenarios and their annual failure probabilities for a specified four compartment building layout

input
$B_1 = \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$ 
N:=4
n[0]:=[1,2,3,4]
output
$P_{fo,\,before,\,1} = poss_{fo,\,1}\,F_1\,P_{lf,\,1}\,P_{fuel,\,1}\,P_{act,\,1}$ $P_{fo,\,before,\,2} = poss_{fo,\,2}\,F_2\,P_{lf,\,2}\,P_{fuel,\,2}\,P_{act,\,2}$ $P_{fo,\,after,\,3} = poss_{fo,\,3}\,F_3\,P_{lf,\,3}\,P_{fuel,\,3}$ $P_{fo,\,after,\,4} = poss_{fo,\,4}\,F_4\,P_{lf,\,4}\,P_{fuel,\,4}$
$P_{fo,\,before,\,1,\,2} = poss_{fo,\,1}\,F_1\,P_{lf,\,1}\,P_{fuel,\,1}\,P_{act,\,1}\,P_{fw,\,1,\,2}\,P_{pass}(2,1)\,P_{fuel,\,2}$ $P_{fo,\,before,\,1,\,3} = poss_{fo,\,1}\,F_1\,P_{lf,\,1}\,P_{fuel,\,1}\,P_{act,\,1}\,P_{fw,\,1,\,3}\,P_{pass}(3,1)\,P_{fuel,\,3}$ $P_{fo,\,before,\,2,\,1} = poss_{fo,\,2}\,F_2\,P_{lf,\,2}\,P_{fuel,\,2}\,P_{act,\,2}\,P_{fw,\,2,\,1}\,P_{pass}(1,1)\,P_{fuel,\,1}$ $P_{fo,\,before,\,2,\,4} = poss_{fo,\,2}\,F_2\,P_{lf,\,2}\,P_{fuel,\,2}\,P_{act,\,2}\,P_{fw,\,2,\,4}\,P_{pass}(4,1)\,P_{fuel,\,4}$ $P_{fo,\,after,\,3,\,1} = poss_{fo,\,3}\,F_3\,P_{lf,\,3}\,P_{fuel,\,3}\,P_{fw,\,3,\,1}\,P_{pass}(1,1)\,P_{fuel,\,1}\,P_{act,\,3}$ $P_{fo,\,after,\,3,\,4} = poss_{fo,\,3}\,F_3\,P_{lf,\,3}\,P_{fuel,\,3}\,P_{fw,\,3,\,4}\,P_{pass}(4,1)\,P_{fuel,\,4}\,P_{act,\,3}$ $P_{fo,\,after,\,4,\,2} = poss_{fo,\,4}\,F_4\,P_{lf,\,4}\,P_{fuel,\,4}\,P_{fw,\,4,\,2}\,P_{pass}(2,1)\,P_{fuel,\,2}\,P_{act,\,4}$ $P_{fo,\,after,\,4,\,3} = poss_{fo,\,4}\,F_4\,P_{lf,\,4}\,P_{fuel,\,4}\,P_{fw,\,4,\,3}\,P_{pass}(3,1)\,P_{fuel,\,3}\,P_{act,\,4}$
$P_{fo,\,before,\,1,\,2,\,4} = poss_{fo,\,1}\,F_1\,P_{lf,\,1}\,P_{fuel,\,1}\,P_{act,\,1}\,P_{fw,\,1,\,2}\,P_{pass}(2,1)\,P_{fuel,\,2}\,P_{fw,\,2,\,4}\,P_{pass}(4,1)\,P_{fuel,\,4}$ $P_{fo,\,before,\,1,\,3,\,4} = poss_{fo,\,1}\,F_1\,P_{lf,\,1}\,P_{fuel,\,1}\,P_{act,\,1}\,P_{fw,\,1,\,3}\,P_{pass}(3,1)\,P_{fuel,\,3}\,P_{fw,\,3,\,4}\,P_{pass}(4,1)\,P_{fuel,\,4}$

$$P_{fo,\,before,\,2,\,1,\,3} = poss_{fo,\,2} F_2 P_{lf,\,2} P_{fuel,\,2} P_{act,\,2} P_{fw,\,2,\,1} P_{pass}(1,1) P_{fuel,\,1} P_{fw,\,1,\,3} P_{pass}(3,1) P_{fuel,\,3}$$

$$P_{fo,\,before,\,2,\,4,\,3} = poss_{fo,\,2} F_2 P_{lf,\,2} P_{fuel,\,2} P_{act,\,2} P_{fw,\,2,\,4} P_{pass}(4,1) P_{fuel,\,4} P_{fw,\,4,\,3} P_{pass}(3,1) P_{fuel,\,3}$$

$$P_{fo,\,after,\,3,\,1,\,2} = poss_{fo,\,3} F_3 P_{lf,\,3} P_{fuel,\,3} P_{fw,\,3,\,1} P_{pass}(1,1) P_{fuel,\,1} P_{act,\,3} P_{fw,\,1,\,2} P_{pass}(2,1) P_{fuel,\,2}$$

$$P_{fo,\,after,\,3,\,4,\,2} = poss_{fo,\,3} F_3 P_{lf,\,3} P_{fuel,\,3} P_{fw,\,3,\,4} P_{pass}(4,1) P_{fuel,\,4} P_{act,\,3} P_{fw,\,4,\,2} P_{pass}(2,1) P_{fuel,\,2}$$

$$P_{fo,\,after,\,4,\,2,\,1} = poss_{fo,\,4} F_4 P_{lf,\,4} P_{fuel,\,4} P_{fw,\,4,\,2} P_{pass}(2,1) P_{fuel,\,2} P_{act,\,4} P_{fw,\,2,\,1} P_{pass}(1,1) P_{fuel,\,1}$$

$$P_{fo,\,after,\,4,\,3,\,1} = poss_{fo,\,4} F_4 P_{lf,\,4} P_{fuel,\,4} P_{fw,\,4,\,3} P_{pass}(3,1) P_{fuel,\,3} P_{act,\,4} P_{fw,\,3,\,1} P_{pass}(1,1) P_{fuel,\,1}$$

$$P_{fo,\,before,\,1,\,2,\,4,\,3} = poss_{fo,\,1} F_1 P_{lf,\,1} P_{fuel,\,1} P_{act,\,1} P_{fw,\,1,\,2} P_{pass}(2,1) P_{fuel,\,2} P_{fw,\,2,\,4} P_{pass}(4,1) P_{fuel,\,4} P_{fw,\,4,\,3} P_{pass}(3,1) P_{fuel,\,3}$$

$$P_{fo,\,before,\,1,\,3,\,4,\,2} = poss_{fo,\,1} F_1 P_{lf,\,1} P_{fuel,\,1} P_{act,\,1} P_{fw,\,1,\,3} P_{pass}(3,1) P_{fuel,\,3} P_{fw,\,3,\,4} P_{pass}(4,1) P_{fuel,\,4} P_{fw,\,4,\,2} P_{pass}(2,1) P_{fuel,\,2}$$

$$P_{fo,\,before,\,2,\,1,\,3,\,4} = poss_{fo,\,2} F_2 P_{lf,\,2} P_{fuel,\,2} P_{act,\,2} P_{fw,\,2,\,1} P_{pass}(1,1) P_{fuel,\,1} P_{fw,\,1,\,3} P_{pass}(3,1) P_{fuel,\,3} P_{fw,\,3,\,4} P_{pass}(4,1) P_{fuel,\,4}$$

$$P_{fo,\,before,\,2,\,4,\,3,\,1} = poss_{fo,\,2} F_2 P_{lf,\,2} P_{fuel,\,2} P_{act,\,2} P_{fw,\,2,\,4} P_{pass}(4,1) P_{fuel,\,4} P_{fw,\,4,\,3} P_{pass}(3,1) P_{fuel,\,3} P_{fw,\,3,\,1} P_{pass}(1,1) P_{fuel,\,1}$$

$$P_{fo,\,after,\,3,\,1,\,2,\,4} = poss_{fo,\,3} F_3 P_{lf,\,3} P_{fuel,\,3} P_{fw,\,3,\,1} P_{pass}(1,1) P_{fuel,\,1} P_{act,\,3} P_{fw,\,1,\,2} P_{pass}(2,1) P_{fuel,\,2} P_{fw,\,2,\,4} P_{pass}(4,1) P_{fuel,\,4}$$

$$P_{fo,\,after,\,3,\,4,\,2,\,1} = poss_{fo,\,3} F_3 P_{lf,\,3} P_{fuel,\,3} P_{fw,\,3,\,4} P_{pass}(4,1) P_{fuel,\,4} P_{act,\,3} P_{fw,\,4,\,2} P_{pass}(2,1) P_{fuel,\,2} P_{fw,\,2,\,1} P_{pass}(1,1) P_{fuel,\,1}$$

$$P_{fo,\,after,\,4,\,2,\,1,\,3} = poss_{fo,\,4} F_4 P_{lf,\,4} P_{fuel,\,4} P_{fw,\,4,\,2} P_{pass}(2,1) P_{fuel,\,2} P_{act,\,4} P_{fw,\,2,\,1} P_{pass}(1,1) P_{fuel,\,1} P_{fw,\,1,\,3} P_{pass}(3,1) P_{fuel,\,3}$$

$$P_{fo,\,after,\,4,\,3,\,1,\,2} = poss_{fo,\,4} F_4 P_{lf,\,4} P_{fuel,\,4} P_{fw,\,4,\,3} P_{pass}(3,1) P_{fuel,\,3} P_{act,\,4} P_{fw,\,3,\,1} P_{pass}(1,1) P_{fuel,\,1} P_{fw,\,1,\,2} P_{pass}(2,1) P_{fuel,\,2}$$

From the constructed event tree in Figure 36 it can be seen that all possible fire spread scenarios are considered in Table 40.

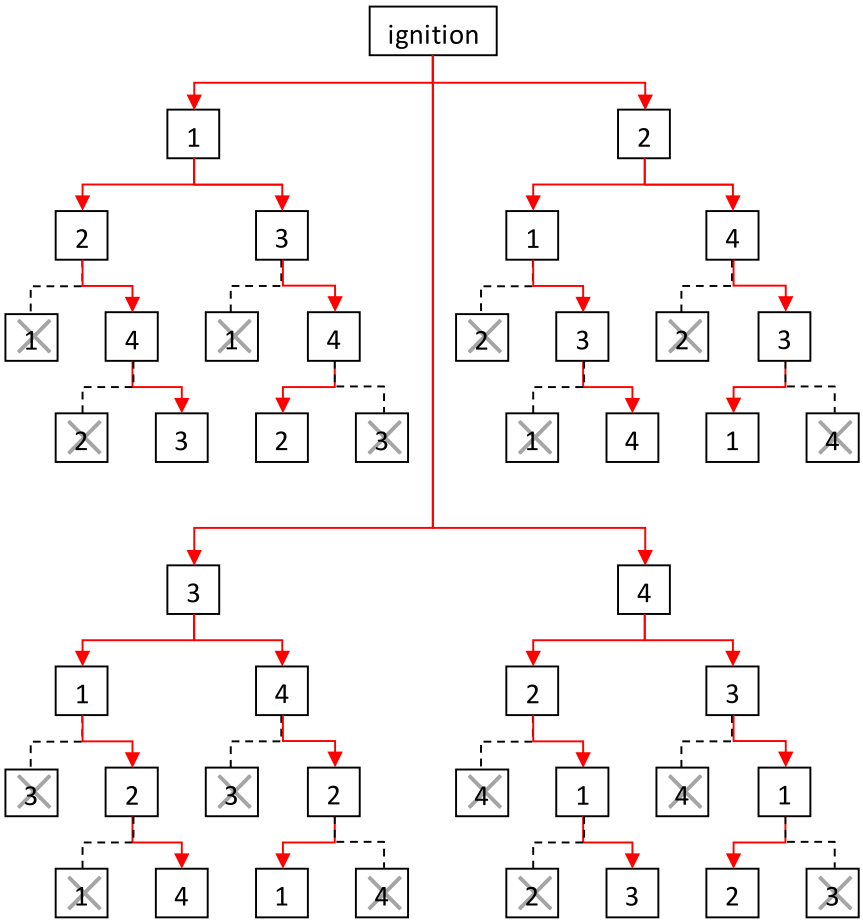


Figure 36: hand calculations, i.e. event tree, to verify the possible fire spread scenarios given by the model in Table 40

Appendix G

Complete list of all used model input parameters

Table 41: Input parameters for the building layout

Variable	*indicator*	*Units*	*Suggested value*
N	Number of compartments	[-]	
n_0	The compartments in which ignition can occur	[-]	
$[B]$	NxN Adjacency matrix for specific for the building layout	[-]	

Table 42: Input parameters for the compartment dimensions

Variable	*indicator*	*Units*	*Suggested value*
$[C_w]$	Nx1 matrix with; $a_{1,1}$ = width of comp. 1 $a_{2,1}$ = width of comp. 2 … $a_{N,1}$ = width of comp. N	[m]	
$[C_l]$	Nx1 matrix with; $a_{1,1}$ = length of comp. 1 …	[m]	
$[C_h]$	Nx1 matrix with; $a_{1,1}$ = height of comp. 1 …	[m]	
$[O_w]$	Nx1 matrix with: $a_{1,1}$ = summation of the vertical opening widths of comp. 1 …	[m]	
$[O_h]$	Nx1 matrix with: $a_{1,1}$ = the averaged vertical opening height of comp. 1 …	[m]	
$[OH_w]$	Nx1 matrix with: $a_{1,1}$ = summation of the horizontal opening widths of comp. 1 …	[m]	
$[OH_l]$	Nx1 matrix with: $a_{1,1}$ = summation of the horizontal opening lengths of comp. 1 …	[m]	

Table 43: Input parameters for the reference situation

Variable	*indicator*	*Units*	*Suggested value*
W_{ext}	Width of the exterior building envelope	[m]	
L_{ext}	Length of the exterior building envelope	[m]	
H_{ext}	Height of the exterior building envelope	[m]	
$[O_{w,ext}\ ]$	Column matrix with: $a_{1,1}$ = width of first vertical exterior opening ...	[m]	
$[O_{h,ext}\ ]$	Column matrix with: $a_{1,1}$ = height of first vertical exterior opening ...	[m]	

Table 44: Input parameters for the cost-benefit analysis

Variable	*indicator*	*Units*	*Suggested value*
γ	Continuous discounting rate	[yr^{-1}]	0.05-0.1 (for private investors)
R_{comp}	Nominal interest rate of compartmentalization	[yr^{-1}]	
t_{max}	Useful life of compartmentalization	[yr]	
M_{comp}	Maintenance cost of compartmentalization	[euro/yr]	
$C_{0,comp}$	Installation cost of compartmentalization	[euro/m$^2_{wall}$]	
$a_{REI,30}$ $a_{REI,60}$ $a_{REI,120}$ $a_{REI,240}$ $a_{REI,360}$ $a_{REI,480}$	Cost scaling factors in function of required REI value	[-]	1 1.1 1.2 1.3 1.4 1.5
$t_{max,spr}$	Useful life of sprinklers	[yr]	
M_{spr}	Maintenance cost of sprinklers	[euro/yr]	
$C_{0,spr}$	Installation cost of sprinklers	[euro/m$^2_{floor}$]	100

Table 45: Input parameters for the maximum possible benefits

Variable	*indicator*	*Units*	*Suggested value*
s_{event}	Possible benefits for total loss scenario	[euro/yr]	
$[s_{whole,i}\ ]$	Nx1 matrix with: $a_{1,1}$ = Possible benefits for comp. 1 ...	[euro/yr]	
$[s_{c,i}]$	Nx1 matrix with: $a_{1,1}$ = Possible benefits per unit floor area for comp. 1 ...	[euro/m^2/yr]	

Table 46: Input parameters for the equivalent time of fire exposure

Variable	*indicator*	*Units*	*Suggested value*
$[q_{f,k}]$	Nx1 matrix where: $a_{1,1}$ = Characteristic fire load density per unit floor area in function of occupancy for compartment 1 …	[MJ/m^2]	
M_{comb}	Combustion factor	[-]	0.8
δ_{ni}	Factor for fire fighting measures	[-]	Table 37
K_c	Correction factor	[-]	Table 39
$[\delta_{q2}]$	Nx1 matrix where: $a_{1,1}$ = factor that accounts for danger of fire activation for compartment 1 in function of the occupation type …	[-]	Table 36
$[\delta_{q1}]$	Nx1 matrix where: $a_{1,1}$ = factor that accounts for danger of fire activation for compartment 1 in function of the floor area ...	[-]	Table 36
λ_{mat}	Thermal conductivity of the material	[W/mK]	0.041
ρ_{mat}	Density of the material	[kg/m^3]	100
δ_{mat}	Physical thickness of the material	[m]	
c_{mat}	Specific heat of the material	[J/kgK]	800

Table 47: Input parameters for the calculation of the HRR and the probability of FO

Variable	*indicator*	*Units*	*Suggested value*
t_E	Arbitrary time for energy release	[s]	200
ρ_{air}	Density of air	[kg/m^3]	1.2
α	Fire growth rate	[kJ/s^3]	Table 7
t_{int}	Intervention time of the fire service	[s]	15*60

Table 48: Input parameters for the calculation of the annual ignition frequency

Variable	*indicator*	*Units*	*Suggested value*
K_1	Factor to determine the annual ignition frequency for industrial buildings based upon the floor area	[m^{-1}*yr^{-1}]	10^{-3}
K_2	Factor to determine the annual ignition frequency for other non-residential buildings based upon the floor area	[m^{-2}*yr^{-1}]	10^{-5}
$\beta_{1,vol}$	Factor to determine annual ignition frequency based upon the building volume	[-]	Table 6
$\beta_{2,vol}$	Factor to determine annual ignition frequency based upon the building volume	[-]	Table 6
$\beta_{1,v}$	Factor to determine annual ignition frequency based upon insured value	[-]	Table 6
$\beta_{2,v}$	Factor to determine annual ignition frequency based upon insured value	[-]	Table 6

Table 49: Input parameters for the fixed probabilities

Variable	*indicator*	*Units*	*Suggested value*
$P_{1,0}$	Failure probability of suppression by occupants and fire service in a very early stage	[-]	0.04
$P_{1,1}$	Failure probability of extra measures in a very early stage	[-]	[2]
P_{spr}	Failure probability of the sprinkler system	[-]	Table 14
P_{det}	Failure probability of the detection system	[-]	Table 14
$[P_{fw}]$	NxN matrix where: $a_{1,2}$ = failure probability of the fire wall between compartment 1 and 2 ...	[-]	
$[P_{pass}]$	Nx1 matrix where: $a_{1,1}$ = failure probability of extra passive measures in comp. 1 ...	[-]	1
$Y(\mu, \sigma)$	Normal distribution to describe the PDF associated with the failure probability of the fire service suppression in function of the fire area	[-]	$\mu = 200$ $\sigma = 40$
$X(\mu, \sigma)$	Normal distribution with mean μ and standard deviation σ to describe the PDF associated with RHR_{max} for a fuel-controlled regime	[-]	$\mu = 250$ $\sigma = 50$

Appendix H

Input and output for comparison with previous model

Table 50: model input and output for comparison with the two compartment scenario of the previous model

variable	*indicator*	*units*	*building*	*comp1*	*comp2*
P[det]	failure probability detection system	[-]	0.25		
P[spr]	failure probability of sprinkler system	[-]	0.02		
t[int]	intervention time fire service	[min]	15		
t[E]	arbitrary time for energy release	[min]	3.3		
N	#comp	[-]	2		
C[w]	width	[m]	50	50	50
C[l]	length	[m]	100	50	50
C[h]	height	[m]	5	5	5
A[f]	floor area	[m^2]	5000	2500	2500
O[w]	vertical opening width	[m]	4	2	2
O[h]	averaged vertical opening height	[m]	1	1	1
par	A[o]*sqrt(H[o])	[m]	4	2	2
A[t]	area bounding enclosure inc. openings	[m^2]	11500	6000	6000
Q[fo]	HRR needed for FO	[kW]	91212	47556	47556
Q[v]	max ventillation contr. HRR	[kW]	6000	3000	3000
V	volume	[m^3]	25000	12500	12500
E	Energy content in the room	[kJ]	51090000	25545000	25545000
t[E]	time needed to release energy content ifo Q[v]	[min]	142	142	142
t[E]/t[arb]	ratio (time needed to release E-content room - arbitrary time)	[-]	42.58	42.58	42.58
/	is FO possible?	[-]	1	1	1
alpha	fire growth rate	[kJ/s^3]	0.047	0.047	0.047
a[f]	fire area at arrival of fire service (if smaller than A[f])	m^2	152	152	152
Q[alpha]	supposed HRR at arrival of fire brigade	[kW]	38070	38070	38070
t[fo]	time to FO	[min]	23	17	17
t[int]/t[fo]	ratio (intervention time - time to FO)	[-]	0.65	0.89	0.89
/	fire service intervention before or after FO?	[-]	before	before	before
F(A)	ignition frequency	[-]	0.05	0.025	0.025
P[lf]	probability that ignition grows to local fire	[-]	0.04	0.04	0.04
P[fuel]	probability that Q[fuel] is bigger than Q[fo]	[-]	1.00	1.00	1.00
P[act]	failure probability of active measures	[-]	0.34	0.34	0.34
FO_prob	probability of FO	[-]	0.01	0.01	0.01
P[fo]	annual probability of FO	[-]	0.000674651	0.000337325	0.000337325
P[fw]	failure probability of fire wall	[-]	0.0005	0.0005	0.0005
P[pass]	failure probability of extra passive measures	[-]	/	1	1
gamma	continuous discount rate	[yr^-1]	0.05		

r	annual discount rate	[yr^-1]	0.051271096		
t[max]	usefull life	[yr]	40		
S	possible benefits	[euro]	5000000	2500000	2500000
M[comp]	maintenance cost	[euro/yr]	0		
REI	required fire resistance	[min]	/	240	240
aa	cost scaling factor ifo REI	/	/	1.15	1.15
C[0,comp]	installation cost	[euro/m^2]	100.00		
C[p]	PV total installation cost	[euro]	28,750.00		
D[p]	PV damage cost	[euro]	29,181.92	14,590.96	14,590.96
B[p]	PV maximum possible benefit	[euro]	58,334.68		
Z[p]	PV total net utility	[euro]	402.76		

Table 51: model input and output for comparison with the four compartment scenario of the previous model

variable	*indicator*	*units*	*building*	*comp1*	*comp2*	*comp3*	*comp4*
P[det]	failure probability detection system	[-]	0.25				
P[spr]	failure probability of sprinkler system	[-]	0.02				
t[int]	intervention time fire service	[min]	15				
t[E]	arbitrary time for energy release	[min]	3.3				
N	#comp	[-]	4				
C[w]	width	[m]	50	25	25	25	25
C[l]	length	[m]	100	50	50	50	50
C[h]	height	[m]	5	5	5	5	5
A[f]	floor area	[m^2]	5000	1250	1250	1250	1250
O[w]	vertical opening width	[m]	8	2	2	2	2
O[h]	averaged vertical opening height	[m]	1	1	1	1	1
par	A[o]*sqrt(H[o])	[m]	8	2	2	2	2
A[t]	area bounding enclosure inc. openings	[m^2]	11500	3250	3250	3250	3250
Q[fo]	HRR needed for FO	[kW]	92724	26106	26106	26106	26106
Q[v]	max ventillation contr. HRR	[kW]	12000	3000	3000	3000	3000
V	volume	[m^3]	25000	6250	6250	6250	6250
E	Energy content in the room	[kJ]	51090000	12772500	12772500	12772500	12772500
t[E]	time needed to release energy content ifo Q[v]	[min]	71	71	71	71	71
t[E]/t[arb]	ratio (time needed to release E-content room - arbitrary time)	[-]	21.29	21.29	21.29	21.29	21.29
/	is FO possible?	[-]	1	1	1	1	1
alpha	fire growth rate	[kJ/s^3]	0.047	0.047	0.047	0.047	0.047
a[f]	fire area at arrival of fire service (if smaller than A[f])	m^2	152	152	152	152	152
Q[alpha]	supposed HRR at arrival of fire brigade	[kW]	38070	38070	38070	38070	38070
t[fo]	time to FO	[min]	23	12	12	12	12
t[int]/t[fo]	ratio (intervention time - time to FO)	[-]	0.64	1.21	1.21	1.21	1.21
/	fire service intervention before or after FO?	[-]	before	after	after	after	after
F(A)	ignition frequency	[-]	0.05	0.0125	0.0125	0.0125	0.0125
P[lf]	probability that ignition grows to local fire	[-]	0.04	0.04	0.04	0.04	0.04
P[fuel]	probability that Q[fuel] is bigger than Q[fo]	[-]	1.00	1.00	1.00	1.00	1.00
P[act]	failure probability of active measures	[-]	0.34	1.00	1.00	1.00	1.00
FO_prob	probability of FO	[-]	0.01	0.04	0.04	0.04	0.04

P[fo]	annual probability of FO	[-]	0.0006747	0.0005	0.0005	0.0005	0.0005
P[fw]	failure probability of fire wall	[-]	0.0005	0.0005	0.0005	0.0005	0.0005
P[pass]	failure probability of extra passive measures	[-]	/	1	1	1	1
gamma	continuous discount rate	[yr^-1]	0.05				
r	annual discount rate	[yr^-1]	0.0512711				
t[max]	usefull life	[yr]	40				
S	possible benefits	[euro]	5000000	1250000	1250000	1250000	1250000
M[comp]	maintenance cost	[euro/yr]	0				
REI	required fire resistance	[min]	/	240	240	240	240
aa	cost scaling factor ifo REI	/	/	1.15	1.15	1.15	1.15
C[0,comp]	installation cost	[euro/m^2]	100.00				
C[p]	PV total installation cost	[euro]	86,250.00				
D[p]	PV damage cost	[euro]	43,276.39	10,819.10	10,819.10	10,819.10	10,819.10
B[p]	PV maximum possible benefit	[euro]	58,334.67				
Z[p]	PV total net utility	[euro]	-71,191.72				

Appendix I

Compartment size of warehouse buildings and the cost of sprinkler installation

Table 52: Estimation of the total number of warehouse buildings in different size categories. Reconstructed from [1]

Size category [m²]	*Size range [m²]*	*Proportion of current stock [%]*	*Estimated number of warehouses**
100	56-178	8.5	2539 ± 810
300	178-560	31.8	9535 ± 2575
1,000	560-1780	36.5	10954 ± 2931
3,000	1780-5600	17.8	5328 ± 1518
10,000	5600-17800	4.7	1419 ± 517
30,000	17800-56000	0.7	224 ± 160
100,000	56000-178000	<0.1	25 ± 50

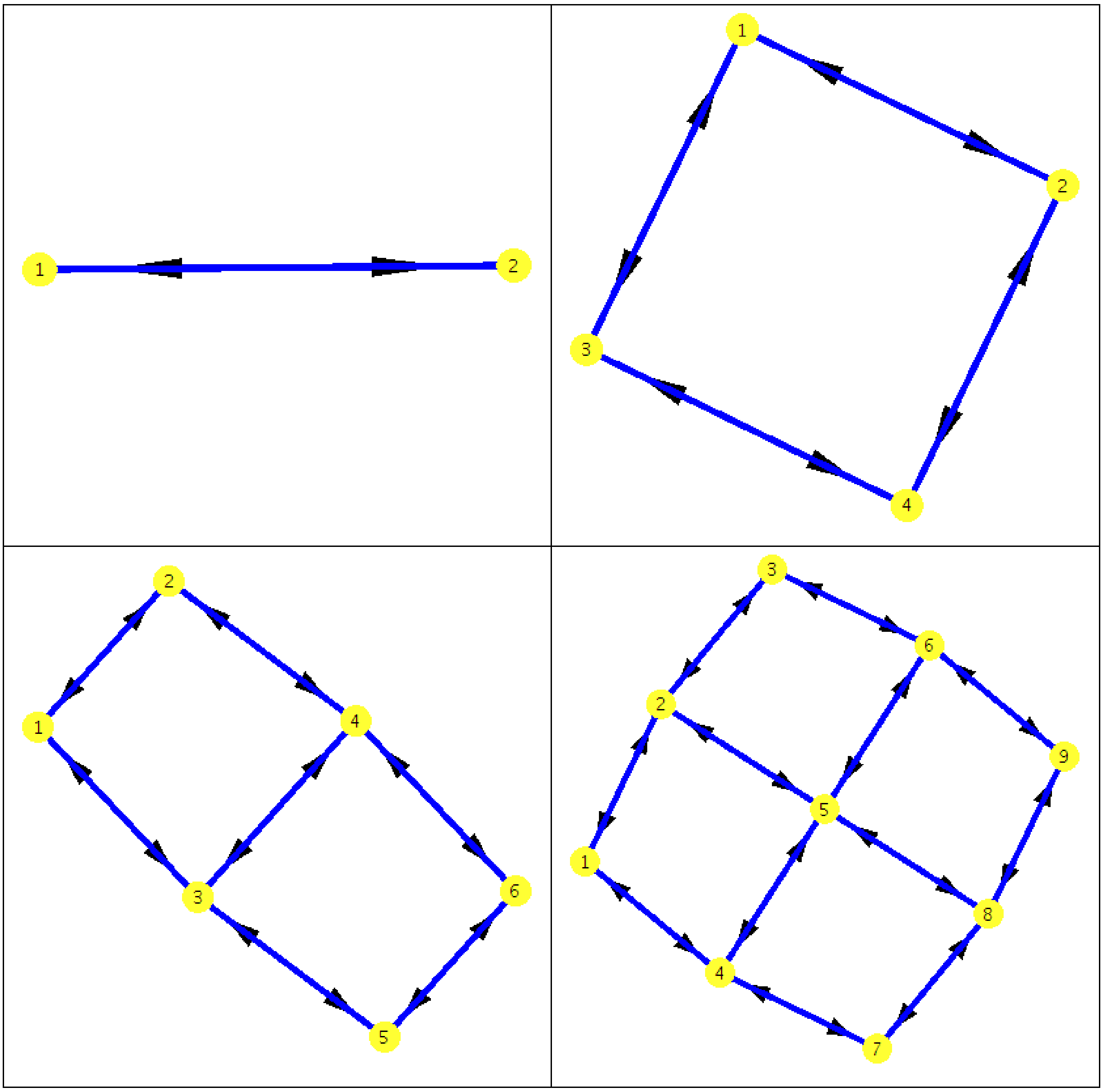
*Uncertainties in the estimated number of warehouses are ± 2 standard deviations

Table 53: Compartment size limitations in other European countries

	Specified maximum compartment size [m²]		
Country	*Not specified hazard*	*Normal hazard*	*Higher hazard*
Denmark	/	5000	2000
France	3000	/	/
Germany	/	1200	400
Netherlands	1000	/	/
Norway	/	1800	1200

Table 54: One-off Installation cost per unit floor area and one-off cost of water supplies for sprinkler installation. Reconstructed from [1]

Sprinkler system	*Small warehouse <1000 m²*		*Medium warehouse 1,000 - 3,000 m²*		*Large warehouse >10,000 m²*	
	inst. [£/m²]	*Water supply [£]*	*Inst. [£/m²]*	*Water supply [£]*	*Inst. [£/m²]*	*Water supply [£]*
No racks	26	30k	24	35k	22.50	42k
Single level in-rack	30	35k	28	38k	27	40k
Two levels in-rack	37	40k	34.50	42k	33.50	45k
Three level in-rack	45	42k	42	45k	41	50k
ESFR at roof level	35	40k	33	42k	32	45k
Average value for CBA	34.60 ± 9.50	37.4k ± 6k	32.30k ± 9.00k	40.4k ± 5k	31.20 ± 9.25	44.4k ± 4k


1
2
1
2
3
4
2
1
4
3
6
5
3
6
2
9
5
1
8
4
7

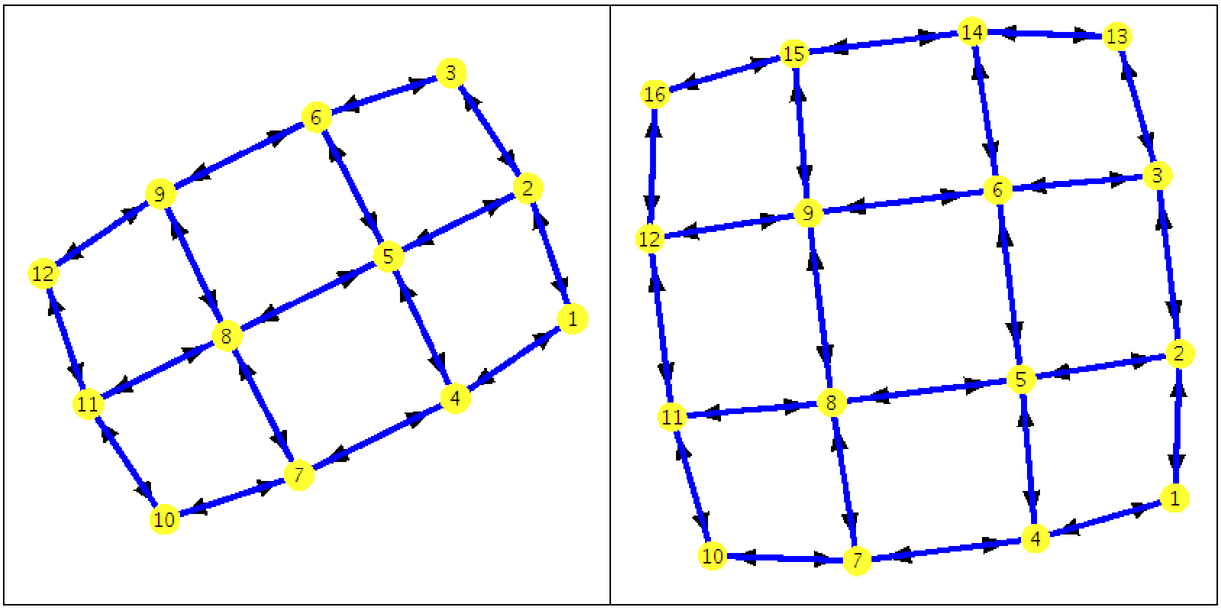


Figure 37: The finite graph interpretations of the buildings layouts, number of compartments N=[2,4,6,9,12,16], used in Section 4.2

Table 55: Calculation of the minimum value per unit floor area needed to return a positive CBA

						CBA[240]				
sc.	*A[f,ext] [m^2]*	*N [-]*	*A[f,i] [m^2]*	*Z(p) [euro]*	*B[p] [euro]*	*C(p) [euro]*	*D[p] [euro]*	*ΔRisk1 [-]*	*s[c,min] [euro/m2]*	*s[c,spr] [euro/m2]*
1.spr	3,000	spr	3,000	-178,985	5,040	183,924	101	4,939	8,936.83	
1.6		6	500	-323,809	5,040	325,347	3501	1,539	50,747.60	-9,980.92
1.4		4	750	-216,806	5,040	216,898	4948	92	566,022.01	-1,632.61
1.2		2	1,500	-111,704	5,040	113,872	2873	2,167	12,610.05	6,065.02
2.spr	10,000	spr	10,000	-388,043	56,001	442,924	1120	54,881	1,936.94	
2.9		9	1,111	-763,631	56,001	792,000	27632	28,369	6,700.20	-3,160.02
2.6		6	1,667	-580,822	56,001	623,700	13124	42,878	3,491.06	-3,614.40
2.4		4	2,500	-378,345	56,001	415,800	18546	37,455	2,664.30	373.57
2.2		2	5,000	-183,819	56,001	207,900	31921	24,081	2,072.04	1,831.31
3.spr	30,000	spr	30,000	-688,993	504,012	1,182,924	10080	493,931	574.78	
3.9		9	3,333	-1,020,251	504,012	1,440,373	83889	420,123	822.83	-837.13
3.6		6	5,000	-694,382	504,012	1,080,280	118114	385,898	671.85	228.03
3.4		4	7,500	-383,089	504,012	720,187	166914	337,097	512.74	708.12
3.2		2	15,000	-143,368	504,012	360,093	287287	216,725	398.77	712.39
4.spr	40,000	spr	40,000	-674,824	896,021	1,552,924	17920	878,100	424.44	
4.9		9	4,444	-916,315	896,021	1,663,200	149136	746,885	534.44	-201.70
4.6		6	6,667	-561,359	896,021	1,247,400	209980	686,041	436.38	381.79
4.4		4	10,000	-232,316	896,021	831,600	296737	599,284	333.04	620.90
4.2		2	20,000	-30,511	896,021	415,800	510732	385,289	259.01	553.78
5.spr	60,000	spr	60,000	-317,198	2,016,047	2,292,924	40321	1,975,726	278.53	
5.9		9	6,667	-356,505	2,016,047	2,036,996	335556	1,680,491	290.91	208.05
5.6		6	10,000	15,845	2,016,047	1,527,747	472455	1,543,591	237.54	424.97
5.4		4	15,000	329,891	2,016,047	1,018,498	667658	1,348,389	181.28	487.56

5.2		2	30,000	357,652	2,016,047	509,249	1149146	866,901	140.98	386.07
6.spr	80,000	spr	80,000	479,478	3,584,083	3,032,924	71682	3,512,402	207.24	
6.12		12	6,667	182,085	3,584,083	2,940,150	461848	3,122,235	226.00	57.07
6.9		9	8,889	635,419	3,584,083	2,352,120	596544	2,987,539	188.95	311.31
6.6		6	13,333	980,073	3,584,083	1,764,090	839921	2,744,163	154.28	396.39
6.4		4	20,000	1,221,076	3,584,083	1,176,060	1186947	2,397,136	117.75	399.59
6.2		2	40,000	953,126	3,584,083	588,030	2042927	1,541,156	91.57	297.67
7.spr	100,000	spr	100,000	1,715,204	5,600,130	3,772,924	112003	5,488,128	164.99	
7.16		16	6,250	1,096,347	5,600,130	3,944,625	559158	5,040,972	187.80	-92.16
7.12		12	8,333	1,821,726	5,600,130	3,068,042	710363	4,889,768	150.59	282.73
7.9		9	11,111	2,038,280	5,600,130	2,629,750	932101	4,668,030	135.20	334.55
7.6		6	16,667	2,315,442	5,600,130	1,972,313	1312376	4,287,754	110.40	360.01
7.4		4	25,000	2,430,650	5,600,130	1,314,875	1854605	3,745,525	84.25	338.53
7.2		2	50,000	1,750,619	5,600,130	657,438	3192073	2,408,057	65.52	242.76

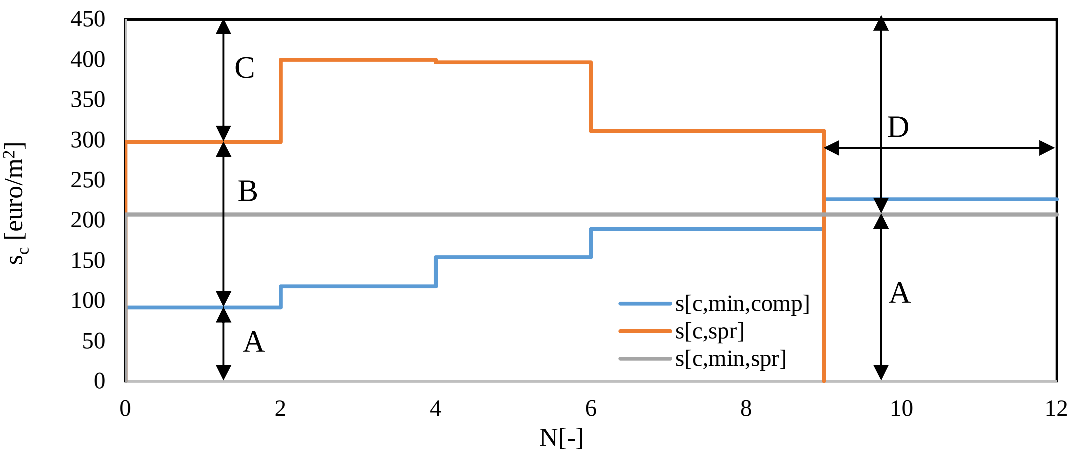


Figure 38: Minimum compartment value per unit floor area needed to make sprinkler and compartmentation installation viable in function of the number of compartments N and for a building floor area $A_{f,ext}$ of 80,000 m^2. [A] indicates the area where both compartmentation and sprinkler are not beneficial, [B] indicates the area where compartmentation returns a greater net utility Z(p) than sprinkler, [C] indicates the area where sprinkler returns the greatest Z(p) and [E] indicates the area where sprinkler return the greatest Z(p) AND risk reduction ΔR

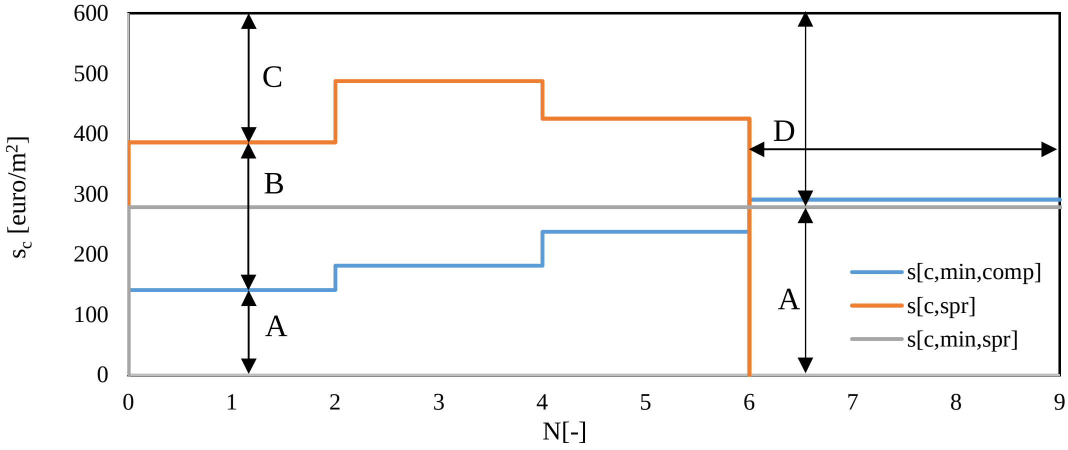


Figure 39: Minimum compartment value per unit floor area needed to make sprinkler and compartmentation installation viable in function of the number of compartments N and for a building floor area $A_{f,ext}$ of 60,000 m^2. [A] indicates the area where both compartmentation and sprinkler are not beneficial, [B] indicates the area where compartmentation returns a greater net utility Z(p) than sprinkler, [C] indicates the area where sprinkler returns the greatest Z(p) and [E] indicates the area where sprinkler return the greatest Z(p) AND risk reduction ΔR

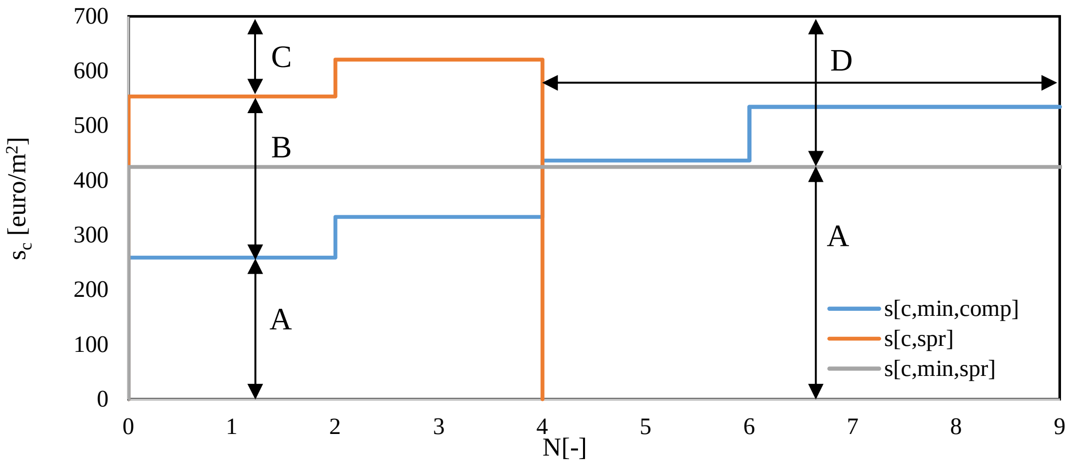


Figure 40: Minimum compartment value per unit floor area needed to make sprinkler and compartmentation installation viable in function of the number of compartments N and for a building floor area $A_{f,ext}$ of 40,000 m^2. [A] indicates the area where both compartmentation and sprinkler are not beneficial, [B] indicates the area where compartmentation returns a greater net utility Z(p) than sprinkler, [C] indicates the area where sprinkler returns the greatest Z(p) and [E] indicates the area where sprinkler return the greatest Z(p) AND risk reduction ΔR