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Fire Dynamics of Multi-Room Compartment Fires

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DOCTORAL THESIS

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Abstract

Fire dynamics in multi-room compartments are explored in this thesis and new methods to study conditions in rooms adjacent to the room of fire origin are presented. Simple and transparent engineering methods can create good possibilities for understanding different complex phenomena present in fire science. Such methods can also be used in the design process in order to perform rough estimates before more advanced and time-consuming analyses are performed. There are several methods available for studying conditions in the room of fire origin. However, there are few methods that can be used to study the conditions in adjacent spaces. This means that there is a need for developing new fire engineering methods for such spaces. In this thesis two such methods are presented and evaluated. A fire in a single room is complex and the problem increases in complexity when multiple rooms are studied. It can therefore be hard to control all influencing variables and to reproduce fire experiments in multi-room compartments. As a part of the exploration of multi-room compartment fires in this thesis, the reproducibility of a full-scale scenario in a typical apartment building is studied. The temperature varied between ±10-35% around the average temperature depending on scenario, location and time after ignition. An alternative to performing traditional experiments is to use numerical experiments. Numerical experimentation is considered to be a promising research method in fire science, and it is evaluated as a part of this thesis.

Key words	
Fire safety engineering, fire dynamics, multi-room compartment, numerical experiment, small-scale experiment, hot-gas-layer temperature, hot-gas-layer interface height, reproducibility	
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Fire Dynamics of Multi-Room Compartment Fires

Nils Johansson

DOCTORAL THESIS

Department of Fire Safety Engineering

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The research that I conducted at the Department of Fire Safety Engineering would not have been possible without the support received from financers, colleagues and family.

Nils Johansson

Lund, March 2015

Summary

Advanced computer models are available for fire safety engineering when a new building is designed and when the fire safety in an existing building is evaluated. Advanced computer models can make good predictions of several factors important for fire safety in buildings and are consequently suitable tools for fire engineering purposes. However, the computer models are complex and can withhold the user information about the calculation process. This can lead to the understanding of the calculations being restricted, and it is therefore important that the user has a fundamental understanding of the underlying fire dynamics of the studied problem. Furthermore, setting up and running computer models can be very time-consuming because it can take several days to get a result. Simple and transparent engineering methods can create possibilities to better understand a complex fire phenomenon and to get an estimate answer rather quickly. Different types of hand-calculation methods are therefore a good complement to the more advanced computer models. Such methods might have a lower accuracy compared to the more advanced computer models but hand-calculation methods can offer a simplified procedure with an approximate answer that is satisfactory for understanding what variables are the most influential and consequently important to determine. Hand-calculation methods can also be used to determine whether a more detailed analysis is needed.

There are a number of hand-calculation methods available for studying conditions in the room of fire origin. However, there are few methods that can be used to study the conditions in adjacent spaces and therefore, in principle, only computer models are used for such analyses. This means that there is a need for developing new hand-calculation methods for this purpose. The topic of this thesis is to explore the area of fire dynamics in multi-room compartments with the explicit objective to develop hand-calculation methods that can be used for such spaces.

Two new hand-calculation methods to study conditions in rooms adjacent to the room of fire origin are presented in this thesis. Both methods are validated against a well-documented experiment that is also included in the thesis. The experiment consisted of 52 individual tests that were performed in a small-scale setup. The first method consists of a correlation derived with the help of empirical data from a numerical experiment and it predicted the hot gas temperature in the adjacent room within 10% of the experimental values. The second method is based on a

mass and energy balance and it consists of several calculation steps. The second method predicted the hot-gas-layer interface height and temperature in the adjacent room within 5 and 30%, respectively, of the experimental values.

Furthermore, the use of numerical experiments in fire science research is evaluated as a part of this thesis work. Numerical experiments are a promising research method that holds both advantages and drawbacks compared to traditional experiments. However, no experimental method can be recommended for all circumstances; therefore, different experimental methods, such as numerical experiments and traditional full-scale experiments, should be seen as complementary rather than competitive.

A fire in a single room is complex and the problem increases in complexity if multiple rooms are studied. It can therefore be hard to control all the influencing variables and to reproduce the experiment. This will lead to some variation in the results between repeated and reproduced tests. Often only single experimental tests are performed with few repetitions. Consequently, knowledge about the magnitude of the variation between reproduced tests is limited. Therefore, as a part of the exploration of multi-room compartment fires, the reproducibility of a typical three-room apartment was studied with the help of 45 full-scale fire tests. Several different ventilation scenarios were studied, and the reproducibility of the temperature measurements, expressed as a 95% confidence interval around the average, varied between ± 10-35% depending on scenario, location and time after ignition.

Five scientific research papers are appended to this thesis. The research in these papers is presented and discussed in the thesis.

Sammanfattning (in Swedish)

Det finns flera avancerade datormodeller att tillgå för att analysera och utvärdera brandsäkerheten i byggnader i samband med nyproduktion och ombyggnad. Denna typ av datormodeller kan, i många fall, göra bra förutsägelser av faktorer som är betydelsefulla för brandsäkerheten och därför är de viktiga verktyg vid brandtekniska analyser. Datormodellerna är dock komplexa och i många fall undanhålls användaren information om själva beräkningsprocessen. Det kan leda till att insynen i beräkningarna blir begränsad och det är därför viktigt att användaren har en grundläggande förståelse för den underliggande brand-dynamiken i det studerade problemet. Beräkningar med hjälp av datormodeller kan även vara tidskrävande eftersom det kan ta flera dagar att få fram ett resultat. Enkla och transparanta handberäkningsmetoder kan däremot skapa möjligheter för att förstå grunderna kring komplexa brandfenomen. De kan även användas för att genomföra tämligen snabba överslagsberäkningar. Olika typer av handberäkningsmetoder är därför ett bra komplement till de mer avancerade datormodellerna. Handberäkningsmetoder har i regel en lägre noggrannhet jämfört med datormodeller, men handberäkningar kan ge ett ungefärligt svar som i många fall kan vara tillfredsställande för att förstå vilka variabler som är mest inflytelserika och därmed viktiga att bestämma. Handberäkningar kan även användas för att avgöra om det, för ett specifikt problem, behövs en mer detaljerad och tidskrävande analys.

Det finns flera enkla handberäkningsmetoder för att studera förhållandena i ett brandrum. Det finns dock få sådana metoder som kan användas för att studera förhållandena i utrymmen angränsande till brandrummet och därför användas i princip endast datormodeller för sådana analyser. Det finns följaktligen ett behov av att utveckla handberäkningsmetoder som är tillämpbara för angränsande utrymmen. Ämnet i denna avhandling är att studera branddynamiken i utrymmen med flera rum, med det uttryckliga målet att utveckla handberäkningsmetoder som kan användas för sådana utrymmen.

Två nya handberäkningsmetoder, för att studera förhållandena i rum som angränsar till ett brandrum, presenteras i avhandlingen. Båda metoderna har validerats mot ett väldokumenterat experiment som även det ingår i avhandlingen. Experimentet bestod av 52 individuella försök i en småskalig uppställning. Den första metoden utgörs av en korrelation som har tagits fram med hjälp av data från

ett numeriskt experiment. Korrelationen visades kunna beräkna brandgas-temperaturen i det angränsande utrymmet inom en avvikelse på 10% från de experimentellt uppmätta värdena. Den andra metoden kan användas för att beräkna brandgaslagrets höjd och temperatur. Metoden bygger på en mass- och energibalans och utgörs av flera beräkningssteg. Metoden predikterade brandgaslagrets höjd och temperatur inom en avvikelse på 5 respektive 30% från de uppmäta värdena i experimentet.

Även användningen av numeriska experiment inom brandteknisk forskning har utvärderats som en del av avhandlingen. Numeriska experiment är en lovande forskningsmetod som inbegriper både för- och nackdelar jämfört med traditionella experiment. Ingen experimentell metod kan rekommenderas för alla tänkbara situationer inom brandteknisk forskning och därför bör experimentella metoder, som numeriska experiment och traditionella fullskaleförsök, inte ses som konkurrerande utan snarare som kompletterande.

En rumsbrand är ett komplext problem och komplexiteten ökar om brandgas-spridning sker till flera rum. När det gäller brandtekniska experiment i verklig skala kan det därmed vara svårt att styra alla variabler som påverkar resultatet och det kan innebära att resultatet varierar mycket mellan reproducerade tester. Ofta genomförs bara enstaka experimentella tester med få upprepningar, följaktligen är kunskapen om den variation som kan förekomma i denna typ av experiment begränsad. Som ett led i studien av branddynamiken i utrymmen med flera rum har därför reproducerbarhet av ett fullskaligt försök i en typisk tre-rums lägenhet studerats med hjälp av 45 experimentella tester. Reproducerbarheten av temperaturmätningarna, utryckt som ett 95% konfidensintervall runt medelvärdet av mätningarna, varierade mellan ± 10-35% beroende på ventilationsförhållande, närhet till branden och tid efter antändning.

Fem vetenskapliga artiklar är bifogade till avhandlingen. Forskningen i dessa artiklar presenteras och diskuteras i avhandlingen.

List of publications

Papers included in the thesis

This thesis is based on five papers that are included in Annex C. Papers I-IV have been accepted for publication in different international scientific journals. Paper V has been submitted for peer review in an international journal. The papers are listed below and the author's contributions to each one of the papers are described in the table on the next page.

Paper I   Johansson, N., Svensson, S. and van Hees, P. (2014) "A study of reproducibility of a full-scale multi-room compartment fire," *Fire Technology*. DOI: 10.1007/s10694-014-0408-3.

Paper II   Johansson, N. (2014) "Numerical experiments and compartment fires," *Fire Science Reviews,* 3(1). DOI: 10.1186/ s40038-014-0002-2.

Paper III   Johansson, N. and van Hees, P. (2014) "A simplified relation between hot layer height and opening mass flow," *Fire Safety Science*. [Published online]. Available at: http://www.iafss.org /publications fss/11/106/view (Accessed: February 18, 2015).

Paper IV   Johansson, N. and van Hees, P. (2014) "A correlation for predicting smoke layer temperature in a room adjacent to a room involved in a pre-flashover fire," *Fire and Materials,* 38(2), pp. 182-193. DOI: 10.1002/fam.2172.

Paper V   Johansson, N., Svensson, S. and van Hees, P. (2015) "An evaluation of two methods to predict temperatures in multi-room compartment fires," submitted to an international journal for peer review.

The author's contributions to the papers are presented in the following table.

Paper	Author's contribution
I	The author performed the analysis and wrote the paper. The author contributed to more than 3/4 of the paper.
II	The paper is based on the licentiate thesis written by the author. The author wrote the whole paper and comments were provided by the author´s main supervisor.
III	The analysis performed in the paper was conducted in a postgraduate course in heat transfer and temperature calculations. The author performed the analysis and wrote the paper. The co-author provided valuable comments on the work.
IV	The author planned and performed the numerical experiment. The author conducted the statistical analysis and wrote the majority of the paper. The author contributed to more than 3/4 of the paper.
V	The author planned and constructed the experimental setup. The author performed the experiment and the analysis presented in the paper. The author wrote the paper. The first co-author provided assistance in the laboratory and during the experiment; the second co-author provided valuable comments on the work.

List of publications not included in the thesis

Publications that are not included in the thesis, but published by the author during his time as a PhD student, are presented below.

Peer-reviewed papers

Johansson, N., Wahlqvist, J. and van Hees, P. (2012) "Detection of a Typical Arson Fire Scenario - Comparison Between Experiments and Simulations," *Journal of Fire Protection Engineering* 22(1), pp. 23-44. DOI: 10.1177/1042391511431508.

Johansson, N., van Hees, P. and Särdqvist, S. (2012) "Combining Statistics and Case Studies to Identify and Understand Deficiencies in Fire Protection," *Fire Technology* 48(4), pp. 945-960. DOI: 10.1007/s10694-012-0255-z.

Kong, D., Johansson, N., van Hees, P., Lu, S. and Lo, S. (2013) "A Monte Carlo analysis of the effect of heat release rate uncertainty on available safe egress time," *Journal of Fire Protection Engineering* 23(1), pp. 1-25. DOI: 10.1177/1042391512452676.

Johansson, N., Wahlqvist, J. and van Hees, P. (2014) "Numerical Experiments in Fire Science - A Study of Ceiling Jets", *Fire and Materials*. DOI: 10.1002/fam.2253.

Johansson, N., van Hees, P., McNamee, S. M., Andersson, P., Jansson, R. and Strömgren, M. (2014) "Technical Measures to Prevent and Mitigate the Consequences of Arson in School Buildings," *Fire Safety Science.* [Published online]. Available at: http://www.iafss.org/publications/fss/11/94/view (Accessed: November 03, 2014).

Nilsson, M., Johansson, N. and van Hees, P. (2014) "A New Method for Quantifying Fire Growth Rates Using Statistical and Empirical Data – Applied to Determine the Effect of Arson," *Fire Safety Science.* [Published online]. Available at: http://www.iafss.org/publications/fss/11/44/view (Accessed: November 03, 2014).

Non peer-reviewed international conference papers

van Hees, P. and Johansson, N. (2010) "Use Of Case Studies To Determine Technical Deficiencies With Respect To Fire Spread In School Buildings," in *12th International Interflam Conference*, Nottingham, England, pp. 1811-1816.

Johansson, N. and van Hees, P. (2011) "Learning from Real Fire Incidents: a Methodology for Case Studies," in *12th International Fire and Materials Conference,* San Francisco, USA, pp. 171-182.

Johansson, N., van Hees, P., McNamee, S. M. and Strömgren, M. (2012) "A Cost-Benefit Analysis of Fire Protection Systems Designed to Protect Against Exterior Arson Fires in Schools," in *9th International Conference on Performance-Based Codes and Fire Safety Design Methods*, Hong Kong, China.

Johansson, N., van Hees, P., Jansson, R. and Sjöström J. (2013) "Behaviour of intumescing systems subjected to different heating conditions," in *13th International Fire and Materials Conference*, San Francisco, USA, pp. 187-196.

Johansson, N., Wahlqvist, J. and van Hees, P. (2013) "Simple ceiling jet correlation derived from numerical experiments," in *13th International Interflam Conference*, London, England, pp. 61-72.

Johansson, N., van Hees, P., McNamee, S. M., Strömgren, M. and Jansson, R. (2013) "Façade Fires in Swedish School Buildings," in *1st International Seminar for Fire Safety of Facades*, Paris, France. DOI: 10.1051/matecconf/ 20130903006.

Johansson, N. and Blomqvist, J. (2014) "Detection of Exterior Fires in Swedish School Buildings", in *15th International Conference on Automatic Fire Detection*, Duisburg, Germany, pp. II:273-282.

Licentiate thesis

Johansson, N. (2013) *Numerical experiments a research method in fire science.* Report 1054, Department of Fire Safety Engineering and System Safety, Lund University, Lund, Sweden.

List of symbols

A_O Area of opening (m^2)

A_T The total surface area, minus area of openings, in a room (m^2)

A_w The total surface area in contact with hot gases in a room (m^2)

C_d Flow coefficient (-)

c Specific heat (kJ/(kg K))

c_p Specific heat at constant pressure (kJ/(kg K))

D_f Diameter of fire source (m)

D Dimensionless variable used in Section 5.1.3, H_D/H_O (-)

d Thickness (m)

g Gravity of earth (m/s^2)

H Room height (m)

H_O Opening height (m)

H_N Height to neutral plane (m)

H_D Height to hot-gas-layer interface (m), see also z_{int}

h Heat transfer coefficient (W/m^2K)

h_k Heat transfer coefficient used in Equations 3 and 14 (W/m^2K)

k Thermal conductivity (W/m K)

L Flame height (m)

l Room length (m)

$\dot{m}_a$ Mass flow rate of ambient air (kg/s)

$\dot{m}_f$ Mass flow rate of fuel (kg/s)

$\dot{m}_g$ Mass flow rate of hot gases (kg/s)

$\dot{m}_p$ Plume mass flow (kg/s)

N Dimensionless variable used in Section 5.1.3, H_N/H_O (-)

$\dot{Q}$ Heat release rate, HRR (kW)

$\dot{Q}_B$ Rate of heat stored in a hot-gas-layer (kW)

$\dot{Q}_c$ Convective part of the heat release rate (kW)

$\dot{Q}_L$ Rate of heat leaving a room due to convective flow (kW)

$\dot{Q}_R$ Rate of heat loss due to radiation through openings (kW)

$\dot{Q}_r$ Radiative part of the heat release rate (kW)

$\dot{Q}_W$ Rate of heat loss to the surfaces in a room (kW)

T_a Ambient temperature (K)

T_g Hot gas temperature (K)

t Time (s)

W Opening width (m)

w Room width (m)

z Height above floor (m)

z_{int} Height to hot-gas-layer interface (m), see also H_D

z_0 Height of virtual origin of fire plume (m)

Greek

β Bias of model predictions compared to experimental data (-)

$\mathcal{E}$ Emissivity (-)

ρ Density (kg/m^3)

σ Stefan-Boltzmann constant (W/m^{2}K^4)

$\tilde{\sigma}_M$ Precision of model predictions compared to experimental data (-)

χ_r Radiative fraction (-)

General Subscripts

1   Property in fire room

2   Property in adjacent room

a   Ambient gas property

g   Hot gas property

HGL   Property of the hot-gas-layer

Terminology

Terms that are used recurrently in the thesis are explained below. The terms are either considered to be unfamiliar with regard to the subject or needing an explanation in the context of this thesis.

Black box testing – an experiment conducted without any hypothesis in order to see how a system responds to manipulation rather than explaining how it works.

Black box effect – when information and control of a calculation process is withheld from the user.

Compartment – a building or a section of a building, e.g. a fire compartment, which can consist of one or several small- or medium-sized rooms.

Compartment fire – fire in a building or a section of a building, e.g. a fire compartment, which can consist of one or several small- or medium-sized rooms. See also Chapter 3.

Conceptual understanding – a comprehension of the basic workings of a phenomenon.

Experiment – a systematic manipulation of variables that influence a certain system in order to evaluate the system response. See also Section 4.1.2.

Method – a collection of procedures or steps, which can include models, to investigate a problem.

Multi-room compartment – a compartment that consists of two or more rooms connected with openings.

Model – a representation of the relevant aspects of a certain system or process.

Model uncertainty – the precision and inaccuracy in the model output compared to some reference data.

Numerical experiment – when a numerical model is used with an experimental approach. See also Section 4.1.2.3.

Table of contents

1 Introduction

Fire safety rules and regulations at city level dates back to the 1300s in Sweden (Fornsvenska textbanken 2015). The regulations were primarily focused on how large fires in the city should be prevented and what actions should be taken if a fire broke out. There were also regulations on the width of streets and alleys in order to prevent fire spread between blocks. However, despite such regulations, several large fires, where whole cities burned down, still occurred in Sweden. For example, the city of Uppsala was almost totally destroyed in 1702 (see Figure 1). Another example is the city of Stockholm where at least 15 severe city fires were documented between 1300 and 1800. The fire safety regulations at city level developed, for instance, an explicit fire regulation was introduced in Stockholm in 1661 (Stockholm Gamlastan 2013). There was even a tradition that the King himself should participate in the fighting of large fires in Stockholm during the 1700s (Friman and Söderström 2012, p. 84).

Figure 1: An illustration of the large fire in the city of Uppsala, Sweden in 1702 (Eenberg 1704). With permission from Kart- och Bildenheten at Uppsala University Libraries.

A comprehensive national fire regulation was introduced in 1874 with requirements for separation of buildings by firewalls or a suitable spacing between in order to prevent the spread of fire (Kongl. Maj:ts 1874). The regulation was prepared as a result of several large-scale city fires in Sweden during the 1800s, where up to 80-90% of the cities were reduced to ashes (Pålsson 2006, p. 6). Until the mid-1900s, local building regulations were allowed in Sweden (Paulsson Hedbäck and Engström 2014, p. 2), but in the 1960s, the building code became national and more demands to divide buildings into fire compartments to limit

the spread of fire and smoke in the building were introduced (Kungliga Byggnadsstyrelsen 1960). Hence, the fire protection in Swedish cites evolved during several hundreds of years from allowing fires to spread between buildings to confining fires to the compartment of origin (see Figure 2).
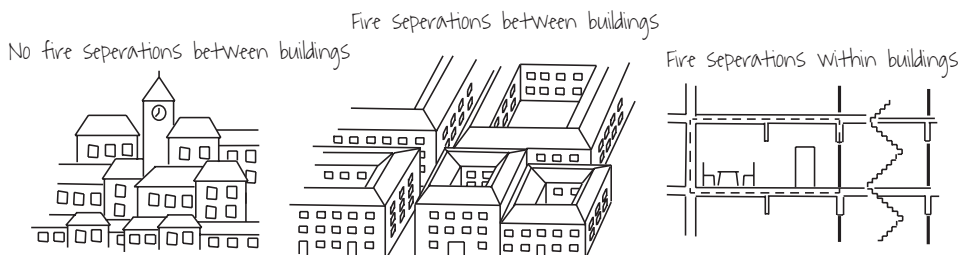
Figure 2: Illustration of how fire protection in cities has evolved.

A fire compartment can contain one or several rooms. The spread of fire and smoke is restricted inside the fire compartment by requirements on surface linings (ceilings, walls and floors), e.g. the Euroclass A-E in the current Swedish building code (Boverket 2014). In some countries, such as the UK, there are also furniture and furnishings regulations (HMG 1988), which contain requirements on ignition resistance of filling materials, upholstery composites and covers in domestic upholstered furniture. However, there are other factors that affect the spread of fire and smoke in a building. One such factor is the geometry of the compartment, e.g. room area, ceiling height and openings between different rooms. In general, no account is taken regarding how the fire compartment geometry and non-fire rated structural elements influence the spread of fire and smoke in prescriptive fire safety designs. In nuclear power plants, however, it is possible to account for the influence of such factors on the hazardous conditions caused by a fire.

The two terms "Fire Compartment" and "Fire Cell" are used in the nuclear industry (IAEA 2004), where "Fire Compartment" refers to what is normally regarded as a fire compartment, e.g. fire separation according to a specific classification. "Fire Cells" is a concept that can be used where it is not possible to establish a conventional fire separation in order to separate a safety system and its redundant part. A "Fire Cell" may consist of an area in a room, one room or several rooms, and a fire compartment can consist of several fire cells. "Fire cells" can, according to a safety guide from the International Atomic Energy Agency (IAEA 2004, p. 12), be created by:

- Minimizing fire load.

- Separating sensitive equipment with a safety distance.

- Passive measures such as fire-resistant walls.

- Active systems, such as sprinkler systems.

- A combination of active and passive measures.

It is possible to place a safety system and its redundant parts in different rooms, but in the same fire compartment, as long as a "Fire Hazard Analysis" shows that sufficient measures are taken to avoid a failure of the system (IAEA 2004, p. 12).

Recommendations for how fire compartments can be divided into smaller elements to reduce the spread of smoke between rooms could be used in comparable industry applications outside the nuclear industry, and also in residential buildings. About 38% of the fire fatalities in apartment buildings in Sweden are found in rooms other than the room of fire origin, but in the same fire compartment (see Figure 3). If the layout and geometry of the rooms in a multi-room apartment are designed with a built-in fire protection system, it could be possibly increase the time to untenable conditions for a specific fire in the apartment. Such a safety system would be more robust than regulations on wall linings and furnishing because it is more difficult for the occupant to move walls and doorframes compared to changing linings and furniture.
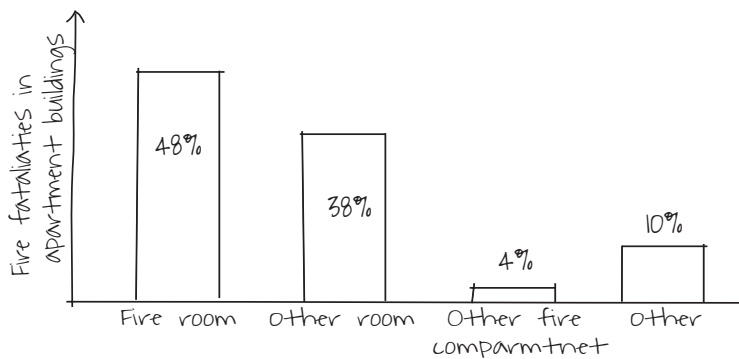
Figure 3: Location of fatalities in Swedish apartment buildings fires in 2005-2013 based on data from Swedish Civil Contingencies Agency (Malmqvist 2014). The category "other" includes the categories "unknown", "outside" and "information missing".

There are no specific recommendations or guidelines in Sweden today for how multi-room compartments can be constructed to reduce the spread of smoke between rooms. However, there is guidance on the internal planning of apartments in the UK. Apartments in the UK can be equipped with a so-called protected entrance hall with the purpose to keep the hall relatively smoke free in the early stages of fire in an adjacent room so people in the apartment can evacuate more easily. All rooms in the apartment should be connected to the entrance hall,

which is separated from the rooms by a 30-minute fire-resisting wall (LG 1994; LG Group 2012)

The existing research on compartment fires generally focuses on the room of fire origin, and in fire science theory is usually the compartment fire referred to as a fire in a single room. There are, of course, examples of experimental studies of multi-room compartment fires. Audouin (2006) carried out a literature review and summarised ten different multi-room compartment fire experiments performed between 1975 and 2005. There are more examples of experimental studies, such as for instance, that by Heskestad and Hill (1986), Nakaya et al. (1986) and Rockett, Morita and Cooper (1989). A multi-room configuration was also used in the PRISME project (Audouin et al. 2013) where heat and smoke propagation through doors, ventilation ducts and leakages in a nuclear facility was studied.

There are several theoretical relationships and engineering methods available for studying conditions in the room of fire origin (Walton and Thomas 2008). However, there is a lack of simple engineering methods that can be used to describe the conditions in rooms adjacent the room of fire origin. This means that studies of the conditions in such spaces need to be conducted with two-zone models or Computational Fluid Dynamics (CFD) models. Such advanced computer models are generally excellent tools for fire engineering purposes, and such models make it possible to estimate hot-gas-layer interface heights, visibility, gas concentrations and temperatures in multi-room geometries. Even so, there is still a need for simple hand-calculation methods for several reasons, which will be explained in the next paragraphs.

A general principle in science, called the principle of parsimony or Occam's razor, is to strive to provide the simplest form of explanation for a given phenomenon and to not add unnecessary assumptions and details (Andersson 2012, p. 74). More details can be added to many models in fire science, but it is not certain that the increased degree in model complexity will be reasonable with regard to the precision or purpose of the model. In the area of structural engineering (Fröderberg 2014), it has been argued that the conceptual understanding of a problem can be negatively affected by use of advanced computer software. Such software, which can include advanced models, might involve concealed processes or so-called "black box effects" that restricts the user information and control of the calculation process. Consequently, the result can be that the user's understanding of the studied problem is inhibited. Lamb (2004) states that understanding of the expected structural behaviour of a element is an essential part of structural modelling and this notion can be translated to the field of fire safety engineering by, e.g., stressing the importance of understanding fire dynamics in order be able to model how smoke will spread in a building. Simple and

transparent methods are considered to be valuable tools in order to understand the fundamentals of complex fire dynamics problems, because such methods include the most important variables that govern the studied phenomenon.

Another reason that supports the use of hand-calculation methods is the possibility for engineers to make estimate calculations in a fire safety design. Simpler methods might have a lower accuracy compared to more advanced methods (two-zone and CFD models), but such simpler methods can provide estimates that can be satisfactory for the studied problem. Rough estimates can also be used to determine if a more detailed and time-consuming calculation using a more advanced model is needed. Furthermore, a simple method can be executed quickly while a CFD model might require hours or days to provide a result. This means that simple methods can provide possibilities to conduct fire risk analyses, e.g. Monte Carlo analyses where hundreds or thousands of scenarios are studied, which is currently not feasible with a CFD model.

Finally, simple methods can be used in parametric studies to increase the knowledge of the factors that determine the conditions in a compartment fire. That could create possibilities to develop recommendations or guidelines for how rooms in a fire compartment should be planned in order to reduce the consequences of fire. As previously mentioned, a robust fire protection can be built into residential buildings in this way.

Thus, there are several reasons for exploring the area of multi-room compartment fires further and the topic of this thesis is therefore fire dynamics in multi-room compartments.

2 Research objective and research questions

It can be concluded, based on the description in Chapter 1, that there is a potential of increasing the knowledge of multi-room compartment fires and to develop new fire engineering methods that can be used to evaluate the conditions in such compartments. In this chapter, a research objective is presented and in order to address this objective, four research questions are formulated.

2.1 Research objective

Multi-room compartment fires are explored in this thesis with the overall objective of developing new, simple and validated hand-calculation methods that can be used to study a number of conditions in rooms adjacent to the room of fire origin in pre-flashover fires.

Based on this overall research objective four research questions (RQ) are formulated and discussed in the following section.

2.2 Research questions

A widely used and often successful approach to finding relationships and models within the field of fire science is to use experimental data. It is generally not easy to derive models for different fire phenomena from fundamental physical principles due to the complexity of the fire phenomena. Therefore, the availability of empirical data has been a crucial element in the development of fire science. For example, experimental tests were used by McCaffrey, Quintiere and Harkleroad (1981) in the development of the well-established MQH-correlation used to calculate temperatures in a single room. A single-room compartment fire is complex and the complexity increases when multiple rooms are studied. This means that it will be more difficult to control all influencing variables in an experiment when the experimental setup increases in size, and it can be harder to reproduce fire experiments in multiple rooms compared to in single rooms. The inability to control an experiment will cause a variation in the results between

repeated or reproduced tests. There are, as mentioned in Chapter 1, several examples of full-scale multi-room compartment fire experiments in the literature. However, due to the rigorous nature and high costs of such tests, experimental fire tests are usually only repeated once or twice, or not at all. Even though there are a few exceptions, e.g Peacock, Davis and Lee (1988). Consequently, the knowledge about the magnitude of the variation between reproduced tests is limited and this forms the origins of the first research question.

RQ1: What reproducibility can be expected in a pre-flashover fire experiment in a multi-room compartment?

The conditions in a multi-room compartment fire will be affected by more variables than in a single-room compartment. The MQH-correlation includes five different independent variables (McCaffrey, Quintiere and Harkleroad 1981), and a rule of thumb is that there should be 10-20 data points for each variable when conducting a regression analysis (Statsoft Inc. 2013). This means that 50-100 data points should be needed to obtain a reasonable correlation with five variables, and one hundred observations are the amount on which the MQH-correlation is based. If a similar correlation was to be created for a two-room configuration, the number of variables would most likely increase. This means that a larger amount of experiments would be needed. Furthermore, a large laboratory would be needed in order to accommodate a full-scale multi-room compartment. Such an experimental test series would be very costly and it does not seem justifiable in order to develop simple hand-calculation methods. Based on this reasoning, the second research question is formulated.

RQ2: What approaches can be applied in order to develop simple hand-calculation methods for calculating conditions in multi-room compartment fires?

A natural extension of RQ2 in line of the overall objective of the thesis is to use the approaches, identified as a result of RQ2, in order to formulate simple hand-calculation methods in terms of algebraic expressions. There are several different criteria that can be used when evaluating fire safety in buildings. Life safety is often evaluated in the pre-flashover stage by calculating the available safe egress time (this will be discussed in Section 3.1). The visibility and exposure of heat and toxic gases are different hazards in a compartment fire that will determine the tenability for occupants (SFPE 2007; Purser 2008). Hazardous gases produced by the pre-flashover fire will be accumulated in the hot-gas-layer, and it is the hot-gas-layer that will determine visibility for occupants. Life safety criteria, with regard to these hazards, applied in calculations to calculate the available safe egress time, are used in fire safety analyses around the world (ICC 2005; SFPE 2007;

Boverket 2013; DBH 2014). The hot-gas-layer temperature will determine the impact of the fire on the room (Dreisbach and Hill 2007, p. 6-3) and the temperature can therefore be considered to be the most important factor with regard to property issues, e.g. the functionality of cables in industries or power plants, in a pre-flashover fire.

In summary, hot-gas-layer interface heights and temperatures are amongst the most important criteria in life safety and property protection analyses in pre-flashover fire safety engineering. It would therefore be desirable to develop methods for calculating these two quantities in multi-room compartments, and this is the motivation for the third research question.

RQ3: How can the hot-gas-layer temperature and interface height in adjacent rooms be predicted with simple hand-calculation methods?

Physical and mathematical assumptions and approximations of the real world are made in models to varying degrees and this will create uncertainties that are difficult to quantify (Hamins and McGrattan 2007). It is, of course, essential for the user of a certain model to know to what degree of accuracy a model can be assumed to predict a certain phenomenon; consequently, it is important to evaluate models in order to quantify the uncertainties associated with them.

There are several guides and standards available for evaluating models (AIAA 1998; ISO 16730 2008; ASTM E1355 2012) and an important part of model evaluation, included in these documents, is to compare model predictions with experimental data with a quantified uncertainty. So, if new models can be developed, they should be evaluated with the help of high quality experimental tests in order to quantify how well the model predictions correspond to such test data.

RQ4: In what order of magnitude are the uncertainties that are associated with the presented hand-calculation methods?

These four research questions are considered to improve the knowledge of multi-room compartment fires in several aspects and thus, the area of multi-room compartment fires can be explored further. The research questions are addressed in Chapter 5 with the help of the research presented in the appended papers.

2.3 Limitations

The topic of this thesis is fire dynamics in multi-room compartments. It involves a comprehensive area, and no attempt is made in this thesis to cover it all. The compartments of focus in this work are apartment-sized compartments with two or three rooms, and not large open-office spaces, retail stores or large public buildings. This thesis works in the paradigm of the well ventilated pre-flashover compartment fire, which is described in more detail in the next chapter.

The thesis is focused on the hot-gas-layer temperature and interface height because these two parameters are commonly used as criteria in life safety and property protection analyses in fire safety engineering. The derived methods are developed for constant heat release rates, and this means that transient conditions are not considered in the methods. Furthermore, the methods have only been evaluated with data from experimental tests that were performed in a small-scale two-room compartment setup.

3 Theoretical background

Fires in buildings can start and develop in many different ways and it will influence the hazardous conditions created. Fires in buildings can be divided into three different categories depending on the characteristics of the building and the enclosure in which the fire is contained (see Figure 4). The first category: "Fires in structural elements" involves fires that start in, or spread to, a structural element e.g. inside walls, attic space, facade or roof. The second category is the so-called "Compartment fire", which involves fires that start in, or spread to, enclosures that are not large in relation to the fire. A hot-gas-layer will form as the fire develops and the temperature throughout the hot-gas-layer will be rather homogenous due to the stirring of the hot gas by the fire. If the fire is small compared to the size of the enclosure there will be large temperature differences within in the hot-gas-layer. This is often the case in the early stages of developing fires. The enclosure can, however, also be so large that it is not reasonable to assume that a homogenous hot-gas-layer will form, and this is the last category of fires, which is referred to as "Fires in large enclosures" in Figure 4. Enclosure fires of this type have sometimes been discussed in the terms of traveling fires (Stern-Gottfried and Rein 2012). The terminology might create a bit of confusion because "Fires in large enclosures" are also fires in compartments but the "Compartment fire" is considered to be an established concept that refers to a model of fires in small- or medium-sized enclosures (e.g. residential rooms, cellular offices, or small industrial units) and therefore, that terminology is used in this thesis.

Torero et al. (2014) discussed fires in buildings and stated that the compartment fire concept is not valid for many modern buildings, but that it is a robust and simple way of describing fire conditions in small enclosures with certain ventilation openings.
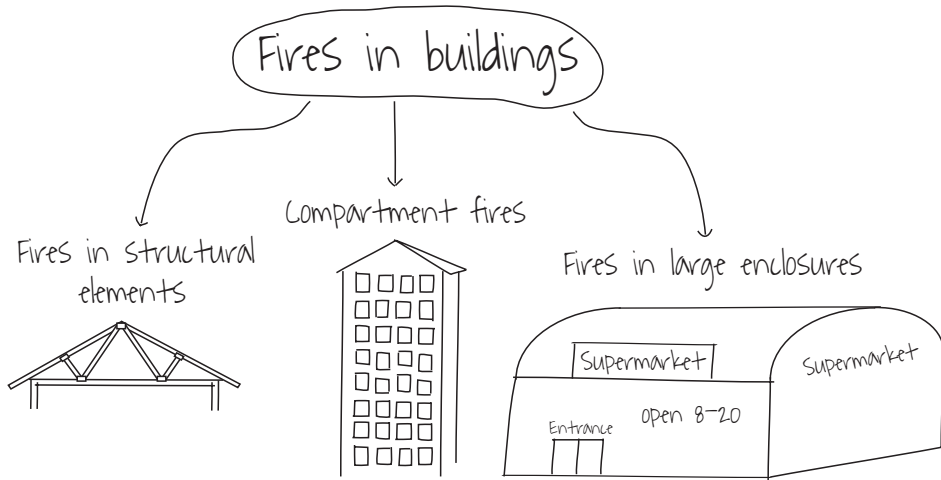
Figure 4: Different categories of fires in buildings.

The three categories constitute an idealisation because the distinctions between the categories are not as clear as illustrated in Figure 4. The categories will overlap and it is possible that several categories may be included in the same fire, e.g. a compartment fire can spread to a structural element or vice versa.

The buildings of focus in this thesis primarily involve apartment-sized compartments, and not large office spaces, retail stores or large public buildings. Thus, this thesis works in the area of the "Compartment fire" and the work presented in this thesis builds on previous knowledge in this area. This chapter is therefore devoted to describing the "Compartment fire" concept and related phenomena. Parts of the text in this chapter are also presented in the appended papers, the present text has however been revised.

3.1 The single-room compartment fire

The compartment fire is described in several modern publications and textbooks on fire dynamics (Karlsson and Quintiere 1999; Quintiere 2006; Drysdale 2011a, 2011b). However, the first comprehensive work on the subject was done by Kawagoe (1958) at the Building Research Institute (BRI) in Japan. Kawagoe studied fully developed fires and summarised a total of ten experiments in rooms with dimensions and fire sizes that resulted in rather homogenous temperatures in the rooms. The work was later extended at BRI (Kawagoe and Sekine 1964; Kawagoe 1967). Thomas (1967) and colleagues (Heselden 1972) conducted extensive studies on fires in rooms, which also should be mentioned in this

context, at the Fire Research Station in the UK concurrently with the work in Japan,

The following equation is normally used to describe the energy balance in a single-room compartment fire.

$$\dot{Q} = \dot{Q}_W + \dot{Q}_R + \dot{Q}_L + \dot{Q}_B \qquad (1)$$

where $\dot{Q}$ is the total heat release rate (HRR) from a fire, $\dot{Q}_W$ is the rate of heat loss to the interior surfaces of the room, $\dot{Q}_R$ is the rate of heat loss due to radiation through openings to the outside, $\dot{Q}_L$ is the rate of heat leaving the room with the combustion gases through openings and $\dot{Q}_B$ is the rate of heat stored in the hot gas. $\dot{Q}_B$ is generally small for slowly growing fires compared to the other components of the equation and is usually omitted under such circumstances.

The temperature development in a typical compartment fire is commonly presented with a graph similar to those in Figure 5 and this idealised fire is usually described as going through the following five stages (Karlsson and Quintiere 1999; Walton and Thomas 2008):

1. Ignition
2. Growth
3. Flashover
4. Fully developed fire
5. Decay

The growth stage and the fully developed fire stage, which often are labelled as the pre-flashover and post-flashover fire, are the stages that, together with flashover, are usually modelled and analysed in fire safety engineering. Flashover constitutes a point between these two stages. Flashover is not a precise term (Peacock et al.1999a), but it is commonly defined as the point when all combustible items in the room become involved in the fire (Walton and Thomas 2008). The room will affect the fire development and changes in insulation, for instance, can yield in major differences in time to flashover (Thomas 1967).
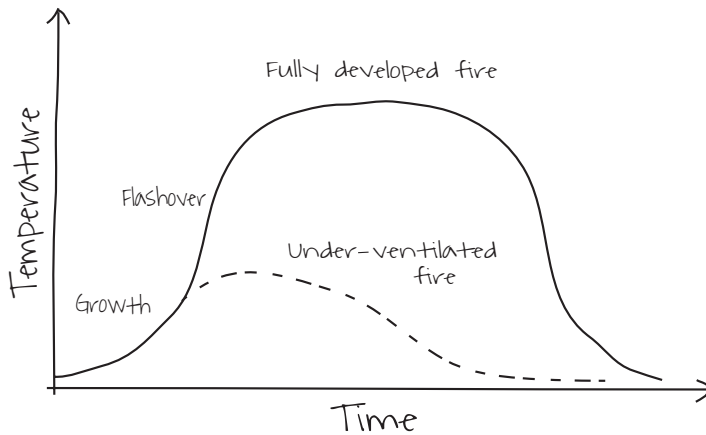
Figure 5: Schematic time-temperature curves of a compartment fire.

The pre-flashover fire is initially well ventilated and it is the characteristics of the fuel that control the burning. The pre-flashover fire is characterized by being stratified into two distinct homogenous layers or zones: an upper layer consisting of hot gases and a lower layer consisting of cooler ambient air. At flashover, the fire changes into being fully developed and there will be a transition from the two-zone case to a one-zone case. The fire can still be well ventilated, if the openings are large; however, the post-flashover compartment fire is often assumed to be ventilation-controlled, i.e. the oxygen available for combustion controls the burning in the room. Combustible gases might leave the room and burn outside the room where oxygen is available. The ventilation-controlled burning can also occur before flashover if the supply of oxygen is limited in the compartment; such conditions are often referred to as under-ventilated fires (see dashed line in Figure 5).

The following two sections are devoted to giving an overview of the current compartment fire theory. The main focus of this thesis is the pre-flashover stage, as mentioned in Sections 2.2 and 2.3. However, for the sake of completeness of the subject of compartment fires, some theory regarding the post-flashover compartment fire is also presented in Section 3.1.2.

3.1.1 Pre-flashover fire

During the pre-flashover fire, life safety is the main concern for fire safety engineering in the compartment of fire origin. In such engineering analyses, the terms "required safe egress time" (RSET) and "available safe egress time" (ASET) are used in designing the building so that RSET ≤ ASET (Mowrer 2008; Drysdale 2011b). As mentioned in Section 2.2, property protection can also be of concern

during the pre-flashover fire. As an example, cables important for operations in an industry or power plant can fail if subjected to high temperatures.

The temperature in both layers will increase in the pre-flashover fire, but the temperature in the upper layer will be much greater (Walton and Thomas 2008). A hot-gas-layer temperature of 600°C will, in general, cause flashover in residential rooms (Hägglund, Jansson and Onnermark 1974) because such high temperatures will cause pyrolysis of most combustible material and furnishing found in buildings. Consequently, the hot-gas-layer temperature in a normal pre-flashover fire will not exceed 600°C.
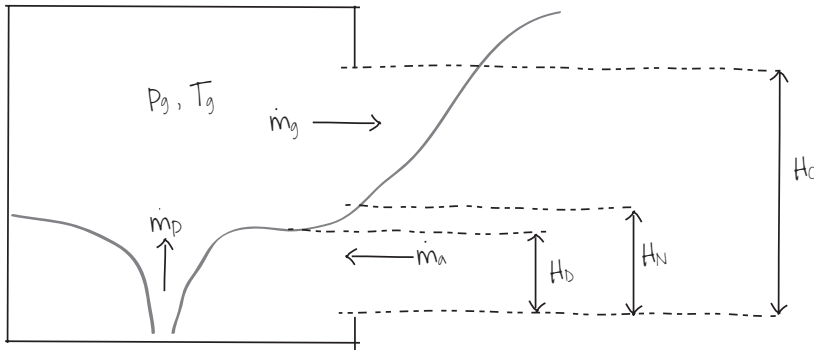
Figure 6: Schematic representation of the two-zone case; the figure is inspired by Karlsson and Quintiere (1999).

The fundamental assumption of the theoretical pre-flashover compartment fire model is that the room can be divided into two distinctly different zones, as shown in Figure 6. H_D is the height above a given reference (e.g. the floor) to the interface between the two zones. This height is referred to as the hot-gas-layer interface height (Karlsson and Quintiere 1999) or the height of thermal discontinuity (Rockett 1976). The neutral plane, H_N, is defined as the height where the pressure difference is zero. The upper and lower zones are assumed to have a uniform temperature, T_g and T_a respectively, and densities, ρ_g and ρ_a respectively. There will be an inflow of gases, $\dot{m}_a$, from the sill to H_N and an outflow of gases, $\dot{m}_g$, from H_N to the soffit H_o. The fire will drive the flow of gases and for a stationary case; it can be assumed that the outflow of gases equals the mass flow of gases entering the hot-gas-layer via the plume, $\dot{m}_p$ (see Equation 2).

$$\dot{m}_g = \dot{m}_p \tag{2}$$

It is possible to calculate $\dot{m}_p$ with the help of established empirical correlations (Heskestad 2008). $\dot{m}_a$ and $\dot{m}_g$ can be calculated using expressions based on the

Bernoulli equation, but it is a tiresome iterative procedure if both H_N and H_D are unknown.

There are several different hand-calculation methods available that can be used to predict hot-gas-layer temperatures in pre-flashover fires (Foote, Pagni and Alvares 1986; Beyler 1991; Walton and Thomas 2008). The most commonly applied and cited method is the previously mentioned MQH correlation (McCaffrey, Quintiere and Harkleroad 1981). The correlation is based on experimental observations and gives the gas temperature increase in a room as a function of the HRR, size of an opening, room geometry and thermal properties of the room boundaries (see Equation 3).

$$\Delta T = 6.85 \left(\frac{\dot{Q}^2}{A_0 \sqrt{H_0} h_k A_T} \right)^{1/3} \tag{3}$$

Predictions with the MQH correlation were compared to experimental data in several studies, e.g. by Deal and Beyler (1990) and Overholt (2014), and it was seen that the correlation gives reasonable temperature estimates and an appropriate description of the physics involved.

Different types of computer models based on the two-zone assumption were found to give a good estimations of the conditions in small- and medium-sized rooms (Karlsson and Quintiere 1999, p. 268). It was also seen in numerical investigations that the effect of vertical density differences in a hot-gas-layer has a limited effect on the doorway mass flow in a room fire (Pretrel et al. 2013). This indicates that the assumption of homogenous temperatures in the hot-gas-layer might have minor effects on the mass flow. The recommended room aspect ratios when using two-zone models like the Consolidated Model of Fire Growth and Smoke Transport (CFAST) are length/width and length/height ratios of less than 3, together with a compartment width/height ratio of at least 0.4. Length/width and length/height ratios of 5 and 6, respectively, and a width/height ratio of at least 0.2 can, however, also be acceptable after special consideration (Peacock, Forney and Reneke 2011, p. 17). Two-zone models are not the focus of this thesis and are therefore not addressed further. More information about two-zone models can be found in, for instance, the CFAST technical documentation (Peacock, Forney and Reneke 2011).

3.1.2 Post-flashover fire

All combustible items in a room will be involved in the fire at flashover and this will cause a transition from the two-zone case into a well-mixed or one-zone case. This is called the post-flashover or fully developed fire.

A different set of engineering models is needed when the post-flashover compartment fire is studied, because the characteristics of the fire are changed. The objective of the engineering analysis is also shifted from life safety towards limiting fire spread, ensuring structural stability and the safety of rescue service personnel (Karlsson and Quintiere 1999, p. 117).
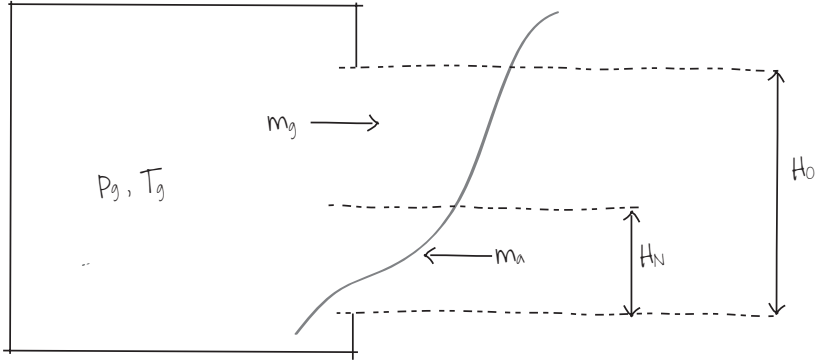
Figure 7: Schematic representation of the one-zone case; the figure is inspired by Karlsson and Quintiere (1999).

The one-zone case is simpler than the two-zone case and it makes it easier to derive simple engineering methods. In the early work at BRI in Japan (Kawagoe 1958; Kawagoe and Sekine 1964), it was found that the burning rate of wood in a post-flashover compartment is proportional to the so-called ventilation factor, which is dependent on the opening size ($A_o H_o^{1/2}$). In the fully developed and ventilation-controlled fire the burning rate will be related to the mass flow of gases entering the opening, which is dependent on the ventilation factor and a constant (see Equation 4). The constant has been found to vary between 0.4 and 0.6 (Rockett 1976), but it is commonly set to 0.5 (Karlsson and Quintiere 1999; ISO 16737 2012).

$$\dot{m}_g = 0.5 \cdot A_o H_o^{1/2} \tag{4}$$

The fully developed fire does however not need to be ventilation-controlled because if the opening increases in size, the fire can pass from being ventilation-controlled to fuel-controlled.

Several different experimental series on post-flashover fires have followed the pioneering work by Kawagoe (1958). Even though the burn rate is not solely dependent on the shape of the opening (Heselden 1961), it has been seen that the ventilation factor and fire load density are important variables in determining the temperatures in ventilation-controlled post-flashover compartment fires. Magnusson and Thelandersson (1970) used these variables to calculate a series of

time-temperatures curves, which later were incorporated as the parametric fire curves in EN 1991-1-2 (2002).

3.2 The multi-room compartment fire

Fires in rooms are usually described as starting in furnishings and then develop by spreading to other items in the room. However, a fire can involve several rooms and there are a few examples of engineering methods to study multi-room post-flashover fires. Harada (2007) described a method of calculating temperatures in fully developed multi-room compartment fires based on an energy balance similar to Equation 1. The method requires sub-models for smoke transport and conduction, which makes the method complicated and not feasible for use in hand-calculations. Another example is the criterion for fire development in multi-room structures presented by Kim and Lilley (2002), which is based on the assumption that the fire spreads to the next room when flashover occurs. Pre-flashover conditions in multi-room compartments seem to have been studied even less, and no hand-calculation methods, comparable to e.g. the MQH-correlation, existed prior to the work by the author.

A general energy balance, similar to Equation 1, can be formulated as in Equation 5 for a multi-room compartment where each room is connected to the next room by an opening and the final room is connected to the outside by an opening (see Figure 8).

$$\dot{Q} = \sum_{i=1}^{n} \dot{Q}_{W,i} + \dot{Q}_L \qquad (5)$$

where $\dot{Q}_{W,i}$ is the heat loss due to conduction through the exterior boundaries in room i and $\dot{Q}_L$ is the convective losses through the opening in the final room. The radiative loss ($\dot{Q}_R$) and the change in energy storage in the hot-gas-layer ($\dot{Q}_B$) are disregarded in Equation 5 because the two included components are considered to be dominating. For slowly-growing or constant fires, $\dot{Q}_B$ can be neglected because the temperature increase in the hot-gas-layer will be small. $\dot{Q}_R$ is considered to be larger than $\dot{Q}_B$, but it is still small in comparison to $\dot{Q}_W$ and $\dot{Q}_L$. The size of $\dot{Q}_R$ in a single-room compartment is evaluated in Annex A in order to illustrate the magnitude of $\dot{Q}_R$ for a simple pre-flashover case.
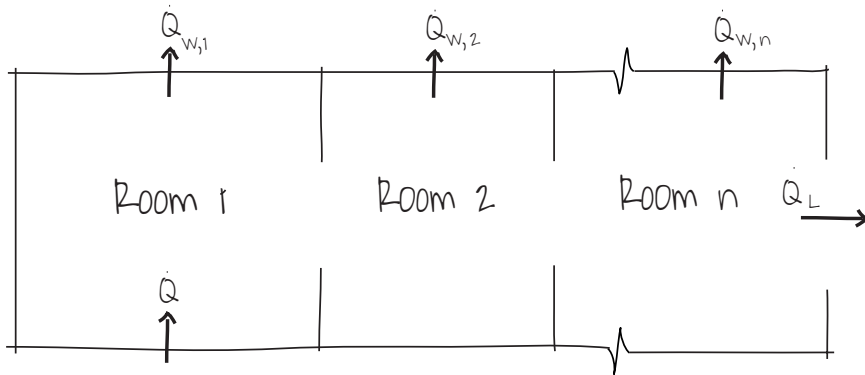
Figure 8: Illustration of a simple energy balance in a multi-room compartment with *n*-number of rooms and with one opening to the outside.

Advanced computer programs, like two-zone models or CFD models, are generally the only tools available to study this type of multi-room scenario.

4 Scientific methodology

There are different possible purposes of research and these are commonly described as being exploratory, descriptive and explanatory (Yin 2003; Robson 2011). The topic of this thesis is to explore the area of multi-room compartment fires. However, the research questions are considered to be descriptive, and there are explanatory parts in the appended papers.

Andersson (2012) presented a framework of the relationship between research questions and types of studies in research. Research questions and the type of study are independent dimensions of research; this means that different types of questions will result in different types of knowledge, and different types of studies will give indications of different types of relationships. Studies can be observational or experimental and the associated research questions can be hypothetical or non-hypothetical (see Figure 9)
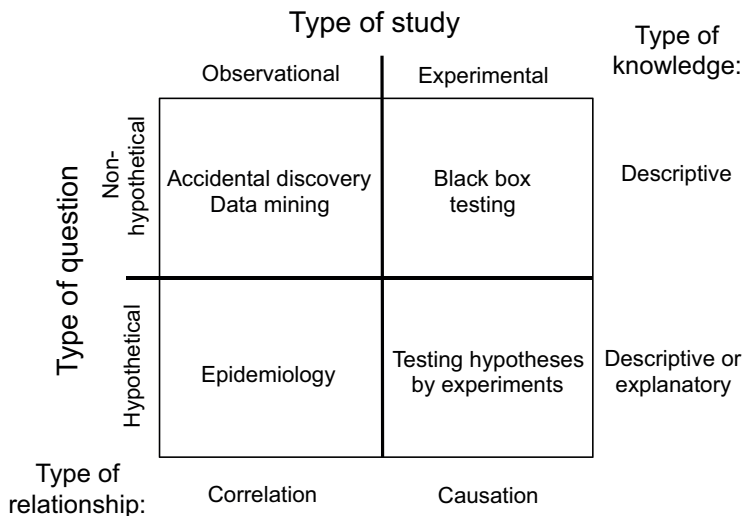
Figure 9: Different types of studies and questions will yield different types of knowledge and relationships, reproduced after Andersson (2012).

In an observational study (left side of Figure 9), a system is studied without being influenced or manipulated by the observer. These observations can be conducted with or without having a hypothesis in mind. When it comes to experimental

research (right side of Figure 9) the type of questions will yield different types of experimental research approaches: "black box testing" and "testing hypotheses by experiments". The latter is conducted when a hypothesis has been formulated and an experiment is designed in order to provide support for the hypothesis. "Black box testing" is more concerned with how the system behaves than how it works and there are no preconceptions about how the system will respond in the experiment. This means that "black box testing" will yield descriptive knowledge, while an experiment that is constructed based on a hypothesis can result in explanatory knowledge. The matrix in Figure 9 illustrates a concept, and there is, of course, a sliding scale between the different types of research rather than the clear demarcation that is illustrated. There is also research that is not possible to place in the matrix, like the research conducted in Papers II and III. Paper II includes a review of previous studies and a qualitative analysis and can, to some extent, be considered as an observational study, but not to the degree that is believed to be meant by Andersson (2012). Paper III includes a review of theoretical relationships and Figure 9 does therefore not cover it. The figure is, however, considered to constitute a good framework to relate the observational and experimental studies conducted in Papers I, IV and V.

It is fundamental that the research results are considered to be trustworthy, independent of the type of study and question. The terms, validity and reliability, are generally used to express the trustworthiness of research. Validity refers to whether the question intended to be answered really is answered, and reliability refers to the consistency or stability of the results (Robson 2011). Validity can be divided into internal and external validity. External validity or generalizability refers to the extent to which the findings could be generalised outside the study. Internal validity refers to the extent to which cause and effect relations can be established (Yin 2003). The validity and reliability of the research results are discussed in Chapter 6.

The different scientific research methods that were used in the papers are presented and discussed in this chapter. The methods are clustered into two different categories: data collection methods (Section 4.1) and data analysis methods (Section 4.2). References are given to the five appended papers throughout this chapter, but the papers will be presented and discussed in detail in Chapter 5.

4.1 Data collection methods

In order to gather information and facts about different process in nature, it is generally necessary to conduct experiments by isolating the process or system of

investigation (Chalmers 1999). However, there are many other possible data collection methods in science and Robson (2011) gives an overview of several of them. The main data collection methods that were applied in the five appended papers are presented in Table 1 and discussed in Sections 4.1.1-4.1.3.

Table 1: An overview of the main data collection methods in the appended papers.

Paper	Main data collection method
I	Observations of full-scale experiments
II	Review of scientific papers
III	Review of theoretical relationships
IV	Numerical experiment
V	Small-scale experiment

4.1.1 Observations

In an observational study, the system under study is not changed and the observer collects data from observations of the system in its pre-existing state and conclusions are drawn based on the observations (Andersson 2012). Examples of observational studies in fire science are studies of real fire incidents. In such studies, the fire event has already occurred and it is not possible for the researcher to intervene.

The advantage of observational studies in fire science is that actual fire incidents occur with some frequency and can consequently provide much data that would have been resource-demanding to collect with traditional experiments. Observations can provide support for correlations between different variables, but it is very difficult to provide support for causation due to the inherent lack of control of the system.

In Paper I, data from full-scale experimental tests are used in what is considered to be an observational study.

4.1.2 Experiments

Andersson (2012) argues that experiments need to be conducted in order to prove causation, because in contrast to observational studies, it is possible to manipulate different independent variables in an experiment (e.g. the HRR or opening size) and that will cause the state of a system (e.g. a compartment fire) to change. That change is measured and analysed in order to generate information that is relevant to a certain research question (see Figure 10) (Johansson 2014). This means that an experiment will include several tests and one or several independent variables are varied between tests. However, an experiment will only provide the

information that it is intended to provide if the setup is appropriate and disturbing factors are eliminated. It is therefore important to have a high degree of control of the experimental tests (Chalmers 1999).
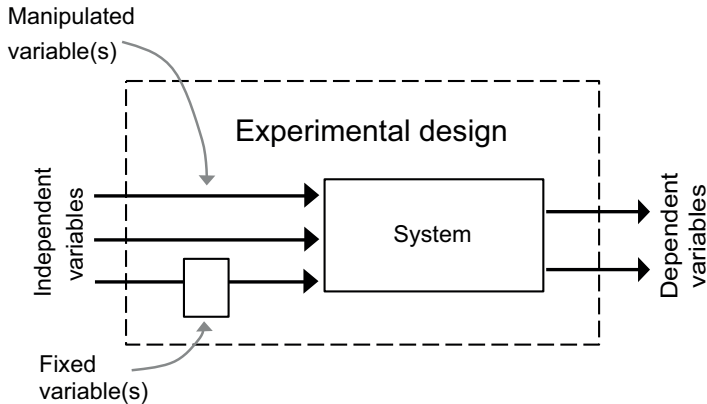
Figure 10: Illustration of an experimental design; the figure is inspired by Höst, Regnell and Runeson (2006).

Three different types of experimental methods have been used to provide data in different ways to the studies in Papers I, IV and V, and these methods are described in the following sections.

4.1.2.1   *Full-scale fire experiments*

A full-scale experiment is a physical experiment that is conducted in the real-scale. The external validity in such experiments is generally considered to be better than in small-scale experiments because the results can more easily be generalized to a situation outside the laboratory. Full-scale setups are used in several standardized test procedures, such as the almost 9 m² large room in ISO 9705 (2001) or the 4 m wide and 6 m high façade in SP Fire 105 (1994). It is also possible to conduct full-scale fire tests of multi-room compartments or even entire buildings in some indoor fire laboratories in the world and Audouin (2006) presents several examples of such experiments.

There are two main problems with full-scale experiments. Firstly, it can be hard to control important variables as the experimental setup increases in size. Thus, the internal validity, i.e. the possibility to demonstrate causal relationships between variables (Robson 2011) can be questioned. It can be even harder to conduct an experiment in an outdoor environment due to the increased number of variables that can influence the experiment, e.g. different weather conditions. The variation between reproduced experimental tests will naturally increase as the number of influencing variables and lack of control of the different variables increase. The

second problem is that full-scale fire experiments are costly and time-consuming. This means that it might not be possible to conduct the number of tests necessary to perform a satisfactory statistical analysis or to repeat a test to get an appreciation of the repeatability.

Despite these issues, full-scale experiments are a very important data collection method in fire science because in many cases, there are no alternatives when complex fire phenomena are under study.

No full-scale experiments have been performed in the appended papers, but it is considered important to describe the data collection method because data from full-scale experimental tests are used in the observational study that is presented in Paper I. Data from previously performed full-scale experiments have also been used in the model evaluations performed in Papers III and IV.

4.1.2.2 Small-scale fire experiments

Realistic fire situations can be scaled down to a smaller size with the help of so-called scaling laws. Dimensional analysis is used to identify the significant dimensionless parameters in order to establish scaling laws for a certain system. These scaling laws are related to the governing laws of physics (Quintiere 1989). By scaling down a compartment fire setup to a suitable size it is possible to conduct the experiment in a controlled laboratory environment. Furthermore, a fire in a small-scale compartment will behave as it does in the real world, i.e. combustion takes place, soot forms and species emerge; thus, the dynamics of the compartment fire are captured (Quintiere 1989, 2006).

Some compromises are necessary in the small-scale experiments because it is not possible to comply with the scaling laws for all the mechanisms of importance in fire science. Complete scaling is not possible for a compartment fire experiment because, for example, heat transfer through radiation, convection and conduction cannot be persevered at the same time. Consequently, some parameters need to be sacrificed, e.g. radiation, when smoke movement from smaller fires are studied, or convection, when large fires are studied (Quintiere 2012). Different dimensionless groups are therefore important for different types of problems. For compartment fires it is appropriate to use the so-called Froude number modelling, i.e. the Froude number is kept constant, in order to study, for instance, gas temperatures (Heskestad 1975). The Froude number represents a relationship between momentum and buoyancy of a flow, and it is important to preserve it when scaling flows driven by natural convection. When using Froude number scaling, it is important that the flow has a turbulent behaviour, i.e. high Reynolds and Rayleigh numbers (Tilley et al. 2013). So the size of the experimental setup must be sufficient to ensure that the flow will be turbulent. Quintiere (2012) states, in

an overview of small-scale compartment fire experiments, that approximately 0.3 m in room height is a minimum to maintain turbulent flow. However, there are, of course, other factors that will also determine the type of flow, e.g. the size of the fire.

Although it is not possible to comply with all the mechanisms of importance in fire science, scaling has several advantages. Small-scale experiments can be conducted at a reduced cost compared to full-scale experiments, and for some specific fire phenomena, the most important variables can be preserved; thus, the negative effect of incomplete scaling is limited. A smaller experimental setup that can be monitored by the researcher is also believed to facilitate for a better control of the experiment (Johansson 2013).

There are several examples where scaling has been used for fire research purposes. An early documented example of the use of small-scale models was conducted at the Fire Research Station (Hird and Fischl 1952) where the fire growth in furnished small-scale rooms was studied. Small-scale models have also been used to derive correlations for different fire phenomena and Quintiere (2006) presents several of these.

A small-scale, two-room compartment fire setup was used in Paper V. The results from the experiment were not scaled up to give a representation of full-scale conditions. Instead, Froude number scaling was used to determine the appropriate size of the HRR that could be used to represent a pre-flashover fire at the $1/4^{th}$ length scale.

4.1.2.3 *Numerical fire experiments*

An alternative to studying a certain fire phenomena with traditional full- and small-scale experiment can be to use a numerical model. All models include, by definition, simplifications of reality, but models can still be used to understand some physical reality (Blurock and Battin-leclerc 2013). Fire models can be used in an experimental manner, i.e. as presented in Figure 10, and such approaches can be referred to as numerical experiments. The author has previously explored the area of numerical experiments (Johansson 2013), and in Paper II, the following definition of numerical experiments in fire science is applied:

"A numerical experiment is performed when a numerical model is used in a systematic experimental approach."

Numerical experiments in the sense of this definition have been applied in different studies in fire science during the last decades (McGrattan, Hamins and Stroup 1998; Prasad, Patnaik and Kailasanath 2002; Chow and Zou 2005; Tilley, Deckers and Merci 2012), but the approach is usually not acknowledged as a

research method comparable to traditional experiments. However, as numerical fire models continuously develop, numerical experiments are becoming an increasingly promising research method in fire science (Johansson 2013).

There are, as with the previously described experimental methods, both advantages and drawbacks in using numerical experiments. The three main advantages stated in Paper II are:

- Numerical experiments are less expensive compared to traditional full- and small-scale experiments. Multiple numerical simulations can be run at the same time if adequate computer resources are available. In contrast, normally only a single traditional experimental test is performed at a time and after each test, the experimental test setup must be reset.

- It is possible to have a high level of control in a numerical experiment and thus, it will be easier to isolate the dependence between different variables. There can be several influencing variables that are unknown or that are impossible to control in a traditional fire experiment.

- Data can be collected in a numerical model without adding instrumentation like thermocouples or bi-directional probes that will influence the measurement. Furthermore, a computer model like the Fire Dynamics Simulator (FDS) (Floyd et al. 2013) does allow for the possibility of recording time-dependent information in all cells used in the domain.

There are also drawbacks in using numerical experiments, and three major drawbacks mentioned in Paper II are:

- The numerical model is a simplification of physical reality. There are several phenomena present in fires, and these are captured in traditional experiments but are not possible to model satisfactorily, e.g. soot formation and fire spread (Quintiere 2012). Numerical experiments must therefore be used carefully because the simplifications included in the applied model may result in the loss of significant information.

- The results are dependent on the different choices made by the researcher and this can be problematic if the researcher is careless or has a limited knowledge of fire dynamics.

- Much validation work on different fire models have been carried out by comparing model predictions with traditional experiments. Even so, the U.S. Nuclear Regulatory Commission (NRC) (Najafi, Jolgar and Dreisbach 2007; McGrattan, Peacock and Overholt 2014) demonstrated that there are just a few models that can predict a handful of output

quantities within the experimental uncertainty of typical compartment fire scenarios.

Numerical compartment fire experiments are discussed in depth in Paper II, and the method has been applied in Paper IV in order to derive a correlation for predicting the hot-gas-layer temperature in a room adjacent to the fire room.

4.1.3 Review techniques

As previously mentioned, the data collection methods used in Papers II and III are not covered entirely by the concepts in Figure 9. The two review techniques that were applied in Papers II and III are different but both are considered to be exploratory.

In Paper II a number of scientific publications are reviewed in order to study how numerical experiments have been used in previous studies. In Paper III the theoretical relationship between the door mass flow and hot-gas-layer interface height in a compartment fire are reviewed in order to retrieve a simplified relation between these two variables.

A general problem with reviews or analyses of work performed by other researchers is that there might be biases in the material and that the purpose of the initial work might not have been the same as that of the intended study (Robson 2011).

4.2 Data analysis methods

Different methods for data analysis were applied in the appended papers. These are presented in Table 2 and discussed in Sections 4.2.1-4.2.4.

Table 2: An overview of the main data analysis methods in the appended papers.

Paper	Main data analysis method
I	Descriptive statistics, functional analysis
II	Qualitative analysis
III	Regression analysis, qualitative analysis
IV	Multiple regression analysis, qualitative analysis
V	Descriptive statistics

4.2.1 Descriptive statistics

Descriptive statistics are used to summarise a data set to one or several single numbers that represent different aspects of the data set. The two aspects that are

most commonly associated with descriptive statistics are known as the measures of central tendency and measures of variability.

The purpose of measures of central tendency is to get a single qualitative number that represents the data set, and this is commonly done with an arithmetic mean, which usually is referred to as the average. Other measures of central tendency are the median and mode (Robson 2011; Statsoft Inc. 2013). However, it can be deceptive to compare two sets of data based only on the central tendency, so it is therefore essential to also study the variation in the data (Körner and Wahlgren 2002).

The difference between individual data points and the mean of the data set is often used to calculate measures of variability. The standard deviation and variance are two widely used measures of variability and these are used in different statistical tests, such as the t-test (Robson 2011).

With the measures of central tendency and variability, a short and useful summary of the main characteristics of the data set can be retrieved (Robson 2007).

Descriptive statistics have been used in Papers I and V. In Paper V, the mean and the standard deviation of the temperature and mass loss rate at two time points were calculated, and in Paper V, the measures were used to quantify the experimental and model uncertainty. The standard deviation was used in both papers to define a 95% confidence interval, which refers to the expected portion of samples that will be contained in a certain interval (Andersson 2012). This made it possible to study the reproducibility of the different scenarios in Paper I and the accuracy of the model predictions in Paper V.

4.2.2 Functional analysis

Graphs are commonly used in fire science to express different quantities; it can be soot concentration over time or temperature as a function of distance from a reference point. When such representations of different measured quantities are compared to predictions from a model, which is commonly done in validation studies, it is frequently done using a subjective and qualitative estimation (Peacock et al. 1999b). However, it is possible to quantify the agreement between different sets of data with the help of so-called functional analysis. The basis of functional analysis is to treat the data sets as multi-dimensional vectors i.e., $x = (x_1, x_2, \ldots x_n)$ with each point in time defining an additional dimension. That makes it possible to quantify the length, angle and distance between two different data sets (Peacock et al. 1999b; ISO 16730 2008). This means that the quantitative comparison does not need to be limited to a single value, e.g. maximum temperature or average velocity, but can be done over the entire data set.

Three functional analysis measures were applied in Paper I in order to study how well each individual test corresponded to the mean of all tests in each scenario. The first measure is the Euclidean Relative Distance (ERD), which is used to quantify the distance between two data sets. An ERD value of 0 indicates that the data sets are identical and 0.1 indicates that there is a 10% difference on average. The second measure gives a value of the shift and it is called the Euclidean Projection Coefficient (EPC). If the calculated EPC value is multiplied by the first data set the best possible agreement to the second data set will be retrieved. The final measure used in Paper I is the Secant Cosine (SC), which gives an estimate of how well the shape of two data sets (or curves) match. An SC value of 1.0 indicates that the shape of the data sets is identical.

Even though functional analysis makes it possible to compare different sets of data quantitatively, it is still necessary to evaluate the calculated values of ERD EPC and SC for the studied problem. However, functional analysis is becoming more important in several different research fields and it has been included as an example validation procedure in ISO 16730 (2008) *Fire safety engineering - Assessment, verification and validation of calculation methods*. A more detailed description of how the three metrics are calculated can be found in Paper I.

4.2.3   Regression analysis

A correlation is a measure that decides the relationship between two or more variables. In a correlation analysis the direction (i.e. whether a certain variable will increase or decrease if another increases) and the strength (i.e. to what degree will the variable be affected) between the variables is analysed. The correlation is expressed by a correlation coefficient, and a correlation of 1 indicates a perfect match. A high correlation between variables does however not mean that there is a causal relationship. A relationship between two variables may occur due to coincidence or due to a common dependence on a third variable (Andersson 2012), this third variable is commonly referred to as a confounding variable.

Regression analyses are used to analyse data in order to find mathematical models for relationships between one or several independent variables and a dependent variable. The simplest regression is linear and is between two variables. Non-linear correlations between a set of independent variables and a dependent variable are more complicated, and for such cases it can be necessary to perform a variable transformation (Andersson, Jorner and Ågren 2007).

The least squared method is commonly used to fit a regression line to a data set, by defining a regression line for which the sum of the residuals (difference between the data and regression line) are minimized (Andersson, Jorner and Ågren 2007). Simply obtaining a regression expression is however not useful if no measure of

the scatter around the line is presented. The scatter can be quantified using the coefficient of determination, R^2, which gives a value of how well the variation in the data is described by the model. Increasing the complexity of the regression expression can increase the R^2-value. A high order equation that follows the observations perfectly is possible to be derived, but that is not considered to be appropriate (Andersson 2012). It would, for instance, not be suitable to try to capture the inherent randomness that is present in a fire experiment with a regression analysis.

There are several issues in linear regression analysis that are necessary to be aware of in order to evaluate if an analysis is properly executed, e.g. there needs to be a linear relationship between the independent and dependent variables and the residuals should be normally distributed. Also, a large set of observations may be needed in order to perform a satisfactory regression analysis, because a rule of thumb is that there should be at least 10-20 data points for each variable when performing a multiple regression analysis. Furthermore, a regression line will only provide a relationship between variables, and can never prove causation (Statsoft Inc. 2013).

Regression analyses have been performed in Papers III and IV. A linear regression analysis between two dimensionless variables was performed in Paper III. In Paper IV, a multiple regression analysis was applied in order to find a relationship for the temperature in an adjacent room based on empirical data from a numerical experiment. After an initial analysis, it was clear that the relationship between the six independent variables, and the dependent variable, was exponential and not linear. Consequently, a variable transformation was needed and a regression analysis was performed with the logarithmic values of the variables.

4.2.4 Qualitative analysis

The data analysis methods described in Section 4.2.1-4.2.3 all have a quantitative nature. Qualitative and quantitative research has traditionally been considered representing different research paradigms. However, qualitative and quantitative research can be combined in multi-strategy research designs (Robson 2011).

An example of a method that can be qualitative is case studies (Yin 2003), where subjective judgment often is used and the findings are expressed verbally. There are several other research methods that can be labelled as qualitative, and are frequently used in research conducted in, e.g., social sciences (Robson 2011).

The use of numerical experiments in fire science is explored qualitatively in Paper II with the help of subjective reasoning and comparisons between traditional experiments and performed numerical experiments. The subjectivity can, of course, create issues with the credibility of the results because the knowledge and

experience of the author affects the analysis and the conclusions drawn. However, it is necessary to perform this type of qualitative analysis in the study because various aspects of numerical experiments and traditional experiments must be weighed against each other. Even though quantitative methods are used in the rest of the appended papers, to some degree, there are qualitative elements in all of them.

A regression analysis can be performed qualitatively by deciding on a best-fit line based on data presented graphically (Robson 2011). It can be useful when more aspects than simply finding a regression line according to the least squared method (see section 4.2.3) need to be considered. Such an approach is applied in Paper III.

Qualitative reasoning can also be used when comparing model predictions with experimental data. As mentioned in Section 4.2.2, functional analysis can be used to obtain quantitative measures of the differences between two data sets. However, it is common that such a comparison is made visually and that the agreement between the two data sets (e.g. two time-temperature curves) is subjectively judged as being, e.g., "satisfactory" or "reasonable". Such graphical and qualitative analyses are performed in Papers III and IV, where model predictions are compared to experimental results without any quantification of the agreement.

5 Research results

The results of the research conducted in this thesis are presented in this chapter. The different data analysis and data collection methods applied in the appended papers were discussed in Chapter 4 and these methods are referred to in Section 5.1 where the papers are presented. In Sections 5.2 and 5.3 the research questions and the research objective are addressed with the help of the papers.

5.1 Presentation of the appended papers

The five appended papers are introduced in this section by presenting the objective and key findings of each paper. Text, figures and equations in this section are, to a large extent, reproduced from the papers and the reader will of course obtain a more comprehensive understanding of the conducted research by reading the papers themselves.

5.1.1 Paper I - A Study of Reproducibility of a Full-scale Multi-Room Compartment Fire.

The objective of Paper I is to quantify the reproducibility of a full-scale test in order to illustrate the possible variability that can be expected in a multi-room compartment fire experiment. The experimental setup was located on the first floor in a three-story mock-up apartment building. The setup consisted of a three-room apartment that was connected to a stairwell. A total of 45 different fire tests, which represented four different ventilation scenarios (see Table 3), were included in the study. The fire source consisted of a pan (Ø=800 mm) filled with heptane that was placed on a load cell centrally in the middle room in the apartment. Temperature measurements were taken using type K thermocouples at four locations in each room and in the stairwell, and the weight of the fire source was recorded. The weather conditions at each test were retrieved from the Swedish Meteorological and Hydrological Institute (SMHI 2014). A more detailed description of the experimental setup is given in Paper I.
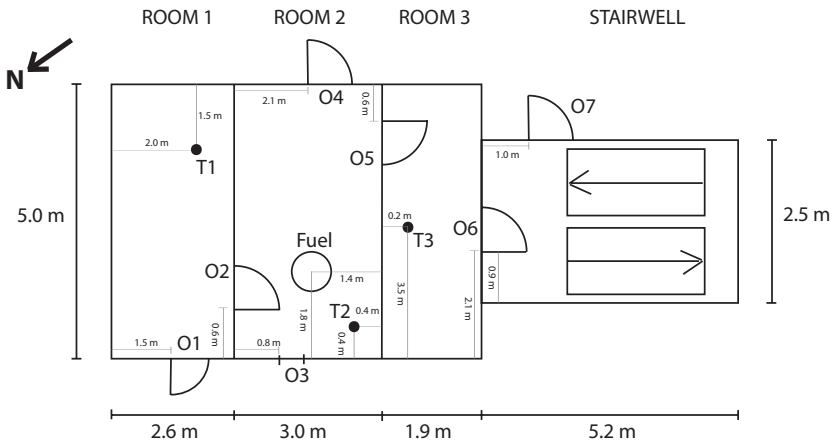
Figure 11: Layout of the three-room apartment. The fire was placed in the middle room.

Table 3: Description of the four studied scenarios.

Scenario	Description
1	Door from room 1 to the outside (O1) was open and door from room 3 to stairwell (O6) was open.
2	Door from room 1 to the outside (O1) was open and door from room 3 to stairwell (O6) was closed.
3	Door from room 3 to stairwell (O6) was open. No other doors were open from the apartment to the outside.
4	Door from room 2 (fire room) to the outside (O4) was open and door from room 3 to stairwell was open (O6).

The fire tests were originally performed as laboratories in a Fire Dynamics course at Lund University and the purpose of the tests were therefore pedagogical and the tests were not planned and executed as an experiment. This means that the system, in terms of the compartment fire setup, were not controlled as needed in order to conduct an experiment according to the description in Figure 10. The tests were performed during a 6-year period and several influencing variables obviously changed between the different tests. The weather conditions (i.e. wind speed, wind direction and humidity) changed between the tests and the exact placement of different measurement equipment varied slightly between the different years. Due to these known variations, it cannot be argued that the repeatability would be tested, because then it is necessary that the same measurement procedure, observer, instruments and location be used (ISO 5725 1994). The term, reproducibility, is instead used because it refers to the agreement of results under some changed conditions of measurement, such as environmental conditions (ISO 5725 1994).

The two most valuable outcomes of Paper I are:

- The observed variation in the different scenarios.

- The possibility of using the data in future evaluations of different fire models.

Descriptive statistics and functional analysis were used to analyse the data in Paper I. The measured temperature (95% confidence interval) in the upper part of the adjacent rooms covered ± 7 to 35% around the average temperature depending on the type of scenario. The temperature variation in the fire room was on average slightly higher. It was also seen that the ventilation conditions affected the reproducibility, e.g. in the scenario with limited ventilation (scenario 3), the reproducibility was poorer.

The original purpose of the tests was not to use them for validation. Nevertheless, the large amount of tests, along with the information about weather conditions, could make it interesting to compare the data with model predictions in future evaluations of fire models.

5.1.2   Paper II - Numerical experiments and compartment fires

Paper II includes a review (see Section 4.1.3) of several scientific papers where numerical experiments were applied and a qualitative analysis with the objective of exploring numerical experiments as a research method in fire science.

Different factors that will influence the accuracy of a numerical experiment are discussed in Paper II, along with advantages and challenges of numerical experiments. The discussion is based on a review and comparison of examples of conducted numerical experiments and traditional full- and small-scale compartment fire experiments. The advantages and challenges associated with numerical experiments, which are discussed in Paper II, have already been covered in Section 4.1.2.3, so the following paragraphs will focus on three factors that influence the accuracy of a numerical experiment.

Firstly, the quality of the input will determine the quality of the output from a model; consequently, the result from a numerical experiment will be dependent on the value of the inputs. There will be uncertainties in the values of the different independent variables (e.g. HRR or room dimensions) included in a traditional experiment. In a numerical experiment, such variables are controlled, and it is possible to be certain of their applied value. However, it is still crucial to use relevant values of the input variables because if the numerical experiment is used to evaluate the relationship between different variables, the relationships found will only be valid for the particular set of values of the inputs used. In such a

situation, it is recommended to perform triangulation with general theories or other empirical data in order to generalise the results. Two examples of the former are: the work by Hwang and Edwards (2005), where the results from a numerical experiment are related to a previously published fire-plume theory, and the work by Johansson, Wahlqvist and van Hees (2014) where a simplified ceiling jet theory is used.

Secondly, the researcher will, of course, have an effect on all types of experiments in terms of how the experiment is arranged. A numerical experiment is even more sensitive to how the researcher executes the study. The researcher needs to be aware of the relevant fire dynamics of the studied problem because the physics can be interfered with in a fire model. For example, different plume models can be selected in a two-zone model like CFAST (Peacock, Reneke and Forney 2012) and the radiation model in FDS (Floyd et al. 2013) can be turned off. It is also possible that the researcher could make mistakes and consequently introduce errors into the numerical experiment. This type of user effects has been seen to be of importance in studies with multiple users (Holmstedt et al. 2008; Audouin et al. 2011).

The final factor mentioned in Paper II, which will influence the accuracy of a numerical experiment, is the accuracy of the fire model used. No attempts are made in Paper II to give an overview of how well validated or verified different models are. However, the general conclusion drawn in the paper is that in hindsight of the currently available validation studies, e.g. by Najafi, Jolgar and Dreisbach (2007) and McGrattan, Peacock and Overholt (2014), the current fire models can only be considered to be appropriate for numerical experiments when studying hot-gas-layer depths and temperatures.

No method can be generally recommended for all possible experimental research tasks in fire science. Both traditional experiments and numerical experiments have their strengths and weaknesses, and they should be seen as complementary rather than competitive. For example, a traditional experiment in small-scale can be complemented with a numerical experiment in real-scale. Another example is when a few traditional experimental tests are complemented with a numerical experiment that includes a larger amount of tests in order to study how the studied system responds to the manipulation of one or several independent variables. With this type of means it is possible to produce convincing and resource-efficient results.

The key findings of Paper II are hard to pinpoint due to the exploratory nature of the paper. Nonetheless, the paper contains valuable contributions because it discusses a research method with a large potential that has been used in fire science for several decades. The paper is also important because research using numerical

models is labelled explicitly as an experimental method and it is discussed on the same terms as traditional experiments. This is believed to be essential with regard to a future discussion about how numerical experiments should be performed and evaluated.

5.1.3 Paper III - A Simplified Relation Between Hot Layer Height and Opening Mass Flow

The mass flow through a door opening from single-room compartment fire is studied in Paper III. The objective is to develop new and simple expressions for the relationship between the mass flow and the hot-gas-layer interface height.

The mass flow leaving a room during a pre-flashover fire, as described in Section 3.1.1, will be dependent on the hot-gas-layer interface height, H_D, the height to the neutral plane, H_N, and the temperature of the hot-gas-layer, T_g. The following two expressions, which can be derived with the help of Bernoulli's equation, can be used to estimate the mass flow entering and leaving a room in a pre-flashover fire.

$$\dot{m}_g = \frac{2}{3} C_d \cdot W \cdot \rho_a \sqrt{2 \cdot g \cdot T_a/T_g \cdot (1 - T_a/T_g)} (H_o - H_N)^{3/2} \qquad (6)$$

$$\dot{m}_a = \frac{2}{3} C_d \cdot W \cdot \rho_a \sqrt{2 \cdot g \cdot (1 - T_a/T_g)} (H_N - H_D)^{1/2} \left(H_N + \frac{1}{2} H_D \right) \quad (7)$$

A description of the derivation of the equations is presented by Karlsson and Quintiere (Karlsson and Quintiere 1999). In the well-mixed case (post-flashover fire) the mass flow entering a compartment can be approximated with a much simpler expression (see Equation 4, Section 3.1.2).

Equation 6 and 7 are not applicable for engineering purposes in the same manner as Equation 4 because H_N and H_D are generally unknown. A computer model is therefore usually required to calculate the mass flow through an opening in a pre-flashover compartment fire. However, two expressions that fill this gap are presented in Paper III. The derivation of the two new expressions is based on the following mass balance.

$$\dot{m}_a + \dot{m}_f = \dot{m}_g \qquad (8)$$

The mass flow rate of the fuel, $\dot{m}_f$, will in most cases be on the order of a few percentages or less of $\dot{m}_a$ (Magnusson 1983, p.26). Consequently, it can be assumed that $\dot{m}_a = \dot{m}_g$, and if Equations 6 and 7 are rewritten with the dimensionless variables: $N = H_N/H_O$ and $D = H_D/H_O$, first introduced by Rockett (1976), the following expression can be retrieved.

$$\left(\frac{1-N}{N}\right)^3 = \left(1 - \frac{D}{N}\right)\left(1 + \frac{D}{2N}\right)^2 \frac{T_g}{T_a} \tag{9}$$

Rockett (1976) previously presented a relationship between D and N for certain values of T_g/T_a graphically. This relationship is investigated further in Paper III and it is evident that the mass flow will be rather independent of T_g/T_a when $T_g/T_a > 1.7$. With the help of a qualitative best-fit analysis (see Section 4.2.4) as illustrated in Figure 12, it is possible to retrieve two approximate expressions (Equations 10a and 10b) for the mass flow.

$$\dot{m}_g/(C_d \cdot W \cdot \rho_a \cdot g^{1/2} \cdot H_o^{3/2}) = 0.26(1 - D) \qquad (D>0.3) \quad (10a)$$

$$\dot{m}_g/(C_d \cdot W \cdot \rho_a \cdot g^{1/2} \cdot H_o^{3/2}) = 0.20(1 - 0.3 \cdot D) \qquad (D<0.3) \quad (10b)$$

Equation 10a is optimized for $T_g/T_a = 1.7$ because it is considered to correspond to a typical pre-flashover temperature and it also gives a fairly good fit for $T_g/T_a \geq 1.5$ as can be seen in Figure 12. Equation 10b is optimised for slightly higher temperatures, i.e. hot-gas-layer temperatures above roughly 200°C. As the hot-gas-layer descends to the floor and D approaches zero, Equation 10b and Equation 4 will give similar results.
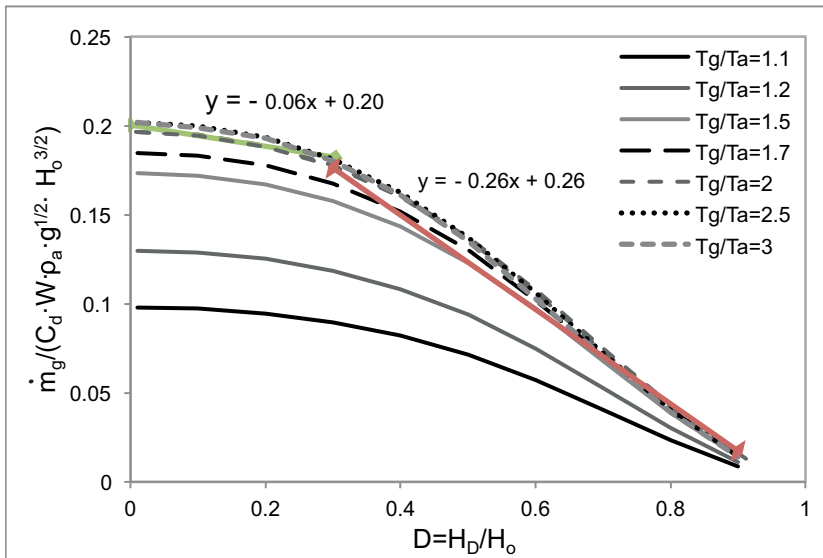
Figure 12: A dimensionless mass flow as a function of hot-gas-layer interface height and temperature. Two best-fit lines are included for $D>0.3$ (red) and $D<0.3$ (green).

If standard values for $C_d = 0.7$, $g = 9.81$ m/s^2 and $\rho_a = 1.2$ kg/m^3 are used, Equations 10a and 10b can be rewritten as follows.

$$\dot{m}_g = 0.684 \cdot A_o \cdot H_o{}^{1/2}(1 - D) \tag{11a}$$

$$\dot{m}_g = 0.526 \cdot A_o \cdot H_o{}^{1/2}(1 - 0.3 \cdot D) \tag{11b}$$

These equations are based on the pre-flashover compartment fire theory (two-zone approximation) that is presented in Section 3.1.1. The equations should work reasonably well for D ranging from 0 to 0.7 and $T_g/T_a > 1.7$ because the error compared to Equations 11a and 11b is less than 10% in this interval.

In Paper III, Equation 11a is compared to predictions by computer simulations using both CFAST (Peacock, Reneke and Forney 2012) and FDS (Floyd et al. 2013), and results from previously performed experiments (Steckler, Quintiere and Rinkinen 1982). The predictions with Equation 11a were within 13% of the simulations and experimental results and the majority of the predictions were within less than 5% (see Figure 13). It is concluded that the agreement is good with regard to the uncertainties that can exist in both computer models and experiments. However, further evaluations of Equations 11a and 11b are recommended in the paper.

Figure 13: The calculated mass flow with Equation 11a compared to data from CFAST, FDS and experiments by Steckler, Quintiere and Rinkinen (1982). The dotted line represents a perfect agreement.

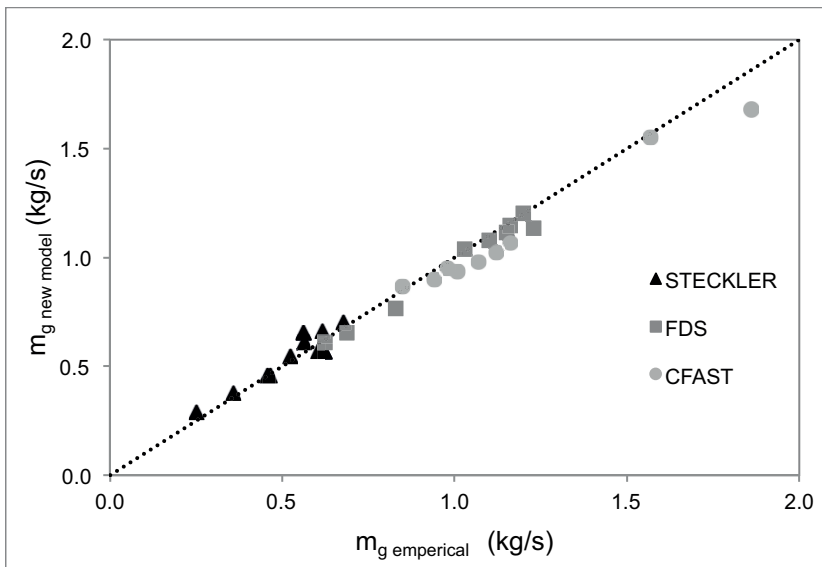It is suggested in the paper that the new expressions could be used to calculate the hot-gas-layer interface height in a room with the help of existing plume models and also to approximate the hot-gas-layer temperature with the help of a simple energy balance such as in Equation 5 (see section 3.2).

Paper III is focused on mass flows from a single room to the outside, which means that the applicability of the expression can be questioned for mass flows between rooms in a multi-room compartment. Previous experimental work (Nakaya et al. 1986) however indicates that the mass flow seems to be similar for openings facing another heated room as when facing an open ambient space. Equation 11a is evaluated in this regard in Paper V when it is applied to calculate hot-gas-layer interface heights in a two-room compartment.

5.1.4 Paper IV - A correlation for predicting smoke layer temperature in a room adjacent to a room involved in a pre-flashover fire

The objective of Paper IV is to develop a correlation for predicting gas temperatures in a room adjacent to a room involved in a pre-flashover fire. The independent variables that are considered to govern the temperature increase in an adjacent room (see Equation 12) can be identified with the help of a simple energy balance (e.g. Equation 5, Section 3.2).

$$\Delta T_2 = f(\dot{Q}, h_k, A_{T,1}, A_{T,2}, A_{O,1}\sqrt{H_{O,1}}, A_{O,2}\sqrt{H_{O,2}}) \qquad (12)$$

$A_{O,1}\sqrt{H_{O,1}}$ and $A_{O,2}\sqrt{H_{O,2}}$ are the ventilation factors between a fire room and an adjacent room, and the adjacent room and an open ambient space. The variables in Equation 12 are treated as independent variables in a numerical experiment conducted in Paper IV. The data from the numerical experiment are used in a multiple regression analysis in order to find a correlation for the hot-gas-layer temperature in the adjacent room.

The numerical experiment was carried out using FDS 5 version 5.5.3 (revision 7069). FDS 5 was shown to predict smoke movement and gas temperatures well in scenarios similar to the studied setup (Najafi, Jolgar and Dreisbach 2007) and the model was therefore considered to be suitable for the intended purpose.

Six variables, which can be identified from Equation 12, were manipulated in the simulations. A script, which was used to generate the input files to FDS, was written in MATLAB. The room dimensions were randomly selected within certain intervals with the restriction that the resulting geometry was within the limits of the two-zone model assumption (see Section 3.1.1). The width and height of the openings were varied between 0.5-2.2 and 1-3.7 m, respectively. The fire source was placed in the centre of the fire room and the HRR was varied between 320 and 2000 kW. The properties of the enclosure boundaries were selected to be similar to concrete, lightweight concrete or brick.

FDS 5 has primarily been validated for well ventilated fires (McGrattan et al. 2010) and only results from such simulations were used in the regression analysis. This resulted in the fact that data from the 86 simulations were generated and a total of 344 observations were available for the regression analysis since data were taken at four time points in each simulation. The length/width and length/height ratio were less than 5 and the compartment width/height ratio was at least 0.5 in the numerical experiment. This is consequently the aspect ratio limits of the resulting correlation.

A multiple linear regression analysis of the logarithmically transformed values of all variables was performed with the statistical software package SPSS. The resulting correlation (see Equation 13) had a coefficient of determination, R^2-value, of 0.93. The non-logarithmic values of the FDS predictions are plotted against the predictions with Equation 13 in Figure 14.

$$\Delta T_2 = 10.4 \frac{\dot{Q}^{0.73}(A_{O,1}\sqrt{H_{O,1}})^{0.24}}{A_{T,1}^{0.45}A_{T,2}^{0.33}(A_{O,2}\sqrt{H_{O,2}})^{0.19}h_k^{0.34}} \qquad (13)$$

Equation 13 can be analysed to determine how different variables influence the temperature in the adjacent room. For instance, it can be seen that the exponent of the HRR is similar to that in the MQH-correlation, where it is 2/3 (see Equation 3, Section 3.1.1).
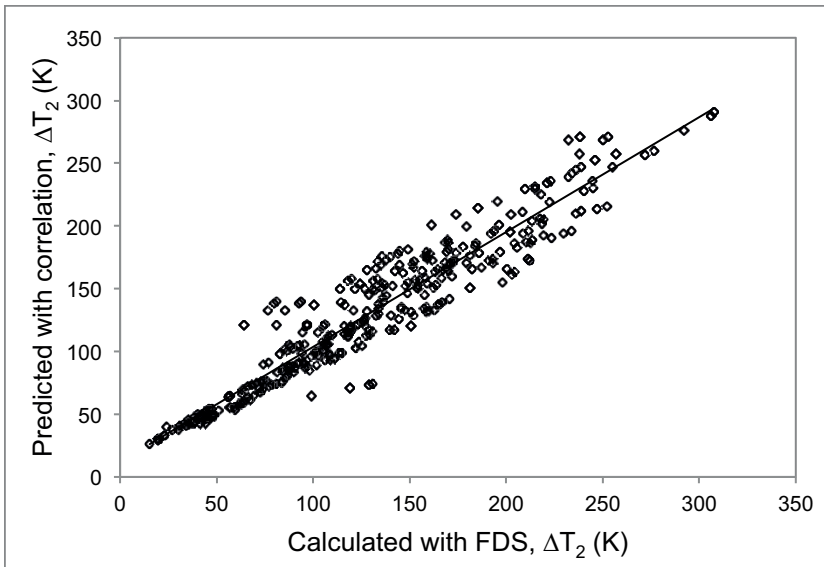
Figure 14: Plot of calculated values with FDS versus predicted value with Equation 13.

The correlation is based on FDS simulations, which means that Equation 13 is a model of a model; consequently, there is a risk that the external validity is poor. Calculations with the Equation 13 were therefore compared to previously published data from three full-scale experiments in Paper IV. The experimental data used accounted for a total of 17 observations. Even though the results were considered to be promising, there were deviations. These deviations could be due to misunderstandings of the experimental setup as a result of the limited information given in the original publications. Nevertheless, further evaluation of the correlation was suggested in the paper.

The major finding in Paper IV is the presented correlation. The correlation was derived through a procedure that resembles "black box testing" and the correlation itself can cause a "black box effect" (see p. 4, Chapter 1), because the physical meaning of the constants related to the different variables in the correlation is unrecognized. However, the correlation provides a rather simple and straightforward method that is a complement to other existing hand-calculation methods.

5.1.5 Paper V - An evaluation of two methods to predict temperatures in multi-room compartment fires

In Paper V, parts of Papers III and IV are linked together. Paper V works, as do Papers III and IV, in the paradigm of the compartment fire (see Chapter 3). Paper V progresses from the same energy balance that is applied in Paper IV and that can be applied in the compartment illustrated in Figure 15.
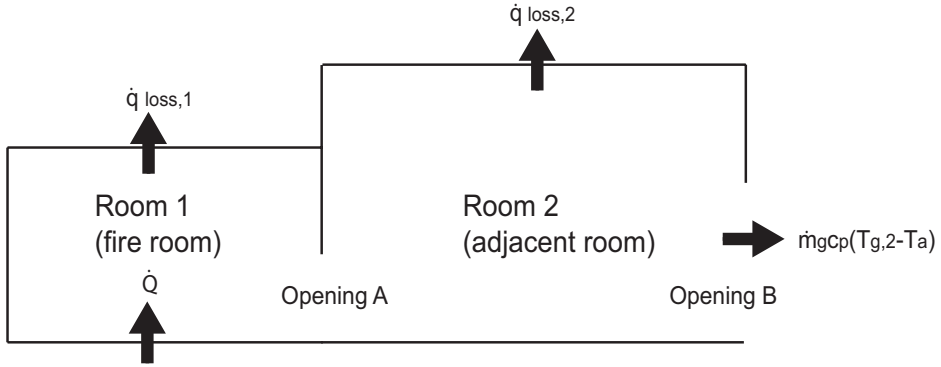
Figure 15: Illustration of an energy balance in a two-room compartment.

The more general energy balance in Equation 5 (see Section 3.2) can be reformulated for the specific case presented in Figure 15 as follows:

$$\dot{Q} = \dot{m}_g c_p \left(T_{g,2} - T_a\right) + \dot{q}_{loss,1} + \dot{q}_{loss,2} \qquad (14)$$

The heat losses to the boundaries in contact with hot gases in each room are expressed using the terms, $\dot{q}_{loss,1}$ and $\dot{q}_{loss,2}$, which in turn can be expressed as being a function of the temperature difference between the boundary surface and the surroundings, the area in contact with hot gases and a heat transfer coefficient (see Equation 15).

$$\dot{q}_{loss,i} = hA_w\Delta\text{T} \qquad (15)$$

Several heat transfer phenomena are lumped into the heat transfer coefficient, h, and it is not trivial to estimate, but it can be done with simplified relationships for semi-infinite or thermally thin materials (Karlsson and Quintiere 1999). An alternative method to estimate the heat transfer coefficient is to use empirically determined values or correlations (Tanaka and Yamada 1999; Veloo and Quintiere 2013; Zhang et al. 2014). A_w is the area in contact with hot gases and no account is taken of the fact that the two rooms have a common wall.

Two methods that can be used to calculate the temperature in the adjacent room are presented in Paper V. The first method (Method 1) includes the correlation presented in Paper IV (see Section 5.1.4). The second method (Method 2) is based on a mass and energy balance and it involves solving Equation 14 in several steps with the help of the simplified expression presented in Paper III (see Section 5.1.3) and an established plume model. A consequence of the many calculation steps in Method 2 is that the hot-gas-layer interface height also will be calculated.

Predictions using the two methods are compared to data from a small-scale compartment fire experiment. By using two different-sized rooms (one small and one larger) in the experiment, two different room configurations could be created. The small room corresponded to a 1/4th-scale ISO 9705 (2001) room, and the large room was 1.2 × 1.2 × 0.8 m. The two rooms were connected with an opening and an opening was also provided from one of the rooms to the outside (see Figure 16). The size of the openings could be varied between a small (0.2 × 0.5 m) and a larger opening (0.3 × 0.5 m). Two different fuels, heptane and methane, with two different heat release rates each, were used in the tests. The fire was placed in the centre of the inner room.

The two room configurations and the two opening sizes were combined into five different geometrical scenarios and by varying the fire source, a total of 16 unique fire test setups were created. These tests were performed 3 or 4 times, and a total of 52 tests were executed in the experiment.

Both rooms were equipped with thermocouple trees (see Figure 16) that were used to approximate the hot-gas-layer interface height and temperature with the help of a data reduction method, which is described further in the paper. The experimental uncertainty for the hot-gas-layer interface height and temperature was estimated by combining estimations of the measurement uncertainty and the model input uncertainty. The position of, and measurements with, the thermocouples were included in the assessment of the measurement uncertainty. The HRR and the heat transfer coefficient were used in the assessment of the model input uncertainty. The relative combined experimental uncertainties for the hot-gas-layer interface height and temperature were concluded to be 13% and 12%, respectively. These are of the same order of magnitude as in previous similar experiments (McGrattan, Peacock and Overholt 2014).
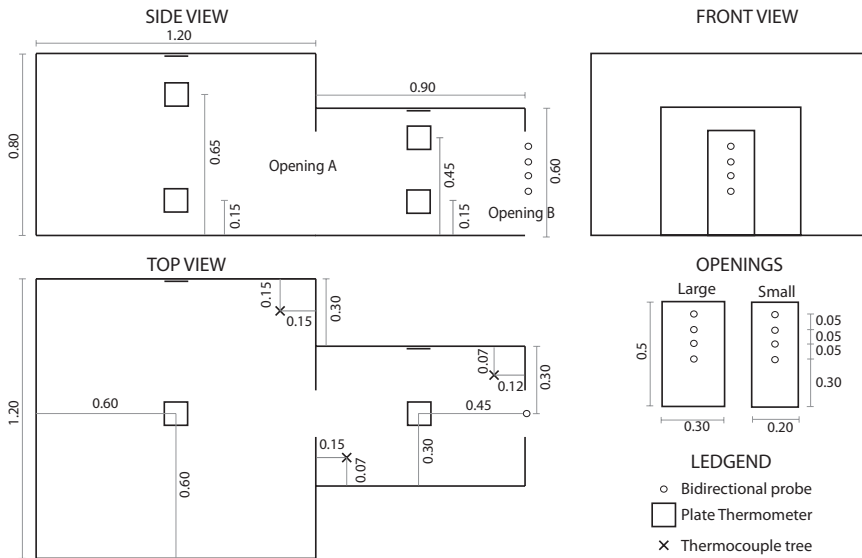
Figure 16: Dimensions and setup in one of the two room configurations in the small-scale experiment. All dimensions are in metres.

Based on the results from the tests and the estimated experimental uncertainties, it was possible to estimate the model uncertainty. The model uncertainty was assumed to correspond to the difference between the experimental measurements and model predictions that could not be explained by the experimental uncertainty. The model uncertainty was expressed by the precision ($\tilde{\sigma}_M$) and bias (β) of the predictions. This procedure of describing model uncertainty was previously used in validation of FDS (Floyd et al. 2013; McGrattan, Peacock and Overholt 2014).

Predictions of the hot-gas-layer interface height and temperature in both rooms are presented in Paper V. Both methods have been used to predict the temperature (see Figure 17) and Method 2 was also used to predict the hot-gas-layer interface height (see Figure 18).
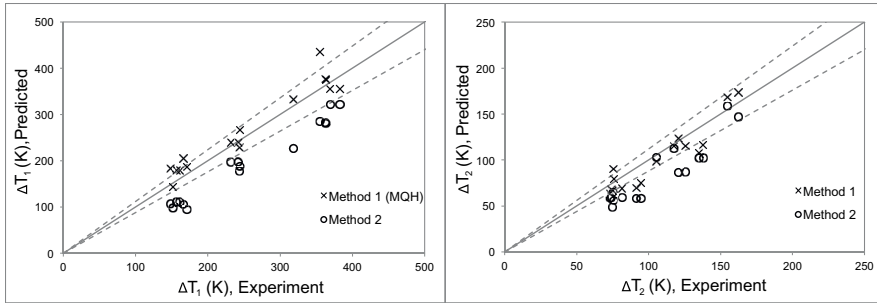
Figure 17: Predicted values plotted against experimental values of the hot-gas-layer temperature for both methods in the fire room (left) and adjacent room (right).
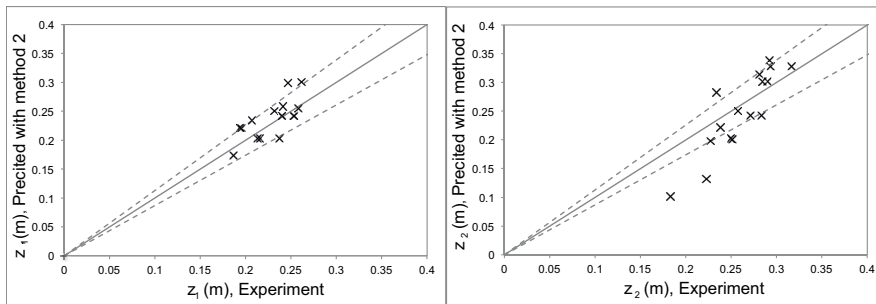
Figure 18: Predicted values plotted against experimental values of the hot-gas-layer interface height for Method 2 in the fire room (left) and adjacent room (right).

Limitations in the experiment and in the models included in the two methods are discussed in Paper V. It is concluded that there are benefits and drawbacks in both methods. Method 1 consists of two simple-to-use and, with regard to the conducted experiment, reasonably accurate mathematical expressions. Method 2 is slightly less accurate than Method 1, but it is more transparent and has a stronger theoretical basis. As mentioned in Section 5.1.4 the procedure that was used to derive Equation 13 can be regarded as "black box testing".

Paper V contains two major research contributions. Firstly, the experimental data are rather comprehensive with a total of 52 performed tests, and the experimental setup, as well as the experimental uncertainty, is described in detail in the paper. Secondly, an evaluation study of two novel methods that can be used to calculate the hot-gas-layer temperature and interface height in a two-room compartment is presented, as well as the precision and bias of the two methods.

5.2 Addressing the research questions

The four research questions that are discussed and formulated in Section 2.2 are addressed in this section with the help of the appended papers.

The relationships between the different papers and research questions in the thesis are illustrated in Figure 19. Paper V is central to the thesis because it has connections to Papers II-IV, which are used to address research questions 2-4. Paper II and IV are related since both deals with numerical experiments. Paper IV is also connected to Paper III in the sense that models, which are used to address RQ3, are developed in both papers. Research question 1 differs slightly from the rest of the questions; however, Paper I is used to address it and at the same time connect it to the rest of the thesis because problems with controlling variables in full-scale experiments is fundamental in the problem description in Paper II.
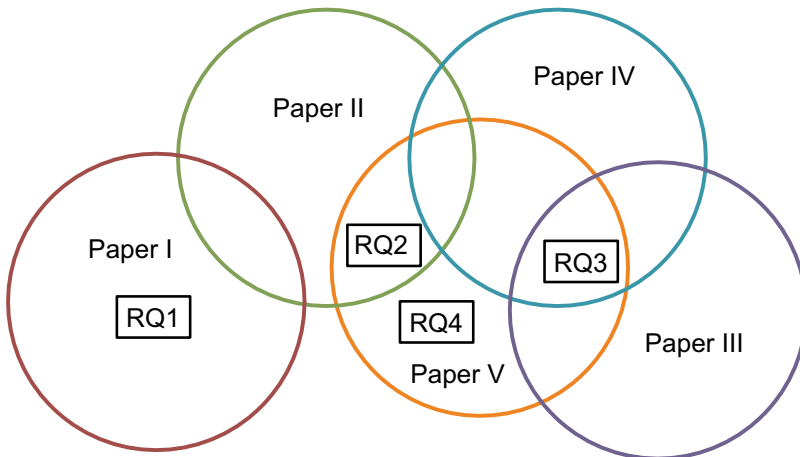
Figure 19: Illustration of how the different research questions (boxes) and papers (circles) are related.

RQ1: What reproducibility can be expected in a pre-flashover fire experiment in a multi-room compartment?

Paper I provides an answer to the first research question with the help of data collected from a full-scale experiment and data analysis with descriptive statistics and functional analysis. The measured temperature intervals (95% confidence interval) in the upper part of the three rooms, studied in Paper I (see Figure 11), are presented in Table 4.

Table 4: The 95% confidence interval (± % around average temperature) observed in Paper I at respectively, 60 and 240 seconds.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Room 1	21 /18	14 / 13	16 / 18	35 / 20
Fire room	26 /19	17 / 22	18 / 33	11 /10
Room 2	22 / 12	11 / 7	21 / 14	21 / 15

The average temperature difference (ERD) in the fire room was higher than in the adjacent rooms, except for scenario 4 in which there was an opening to the outside. The correspondence between the shapes of the individual and average time-temperature curves (SC value) was consistently poorest in the fire room (0.7-0.85) while it was close to 1 (0.95-0.98) in the adjacent rooms. The average temperature difference (ERD) and shift (EPC) in the fire room was largest when the ventilation was limited, which occurred during the later stage of scenario 3 in which there was no opening to the outside in any of the three rooms. In general, for the other scenarios, the variation was smaller in the later stage when the temperature increase levelled off.

Based on the results in Paper I, it is considered reasonable to expect a temperature variation in the hot-gas-layer, expressed as a 95% confidence interval, in the magnitude of ± 10-35% in this type of full-scale experiment. The variation will be dependent on ventilation conditions and also on location (fire room or adjacent room) and time after ignition.

RQ2: What approaches can be applied in order to develop simple hand-calculation methods for calculating conditions in multi-room compartment fires?

It is not reasonable to derive simple mathematical expressions for estimating compartment fire temperatures in an adjacent room directly from theory, due to the complexity of the fire phenomena as previously mentioned in Section 2.2. Two different alternative approaches have been used in the appended papers in order to develop two different hand-calculation methods. The methods are based on the simplified energy balance presented in Section 3.2; however, the approaches used to derive the methods are different (see Figure 20).
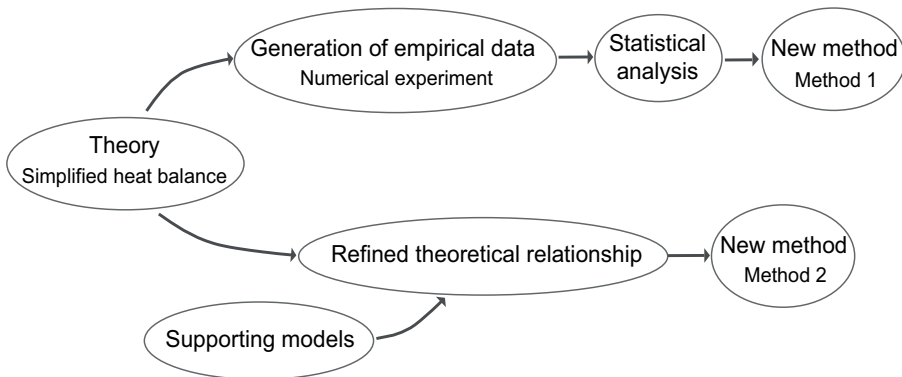
Figure 20: The two different approaches used in the thesis work to derive the two methods for calculating temperatures in a room adjacent to a fire room.

In the first approach, the top branch in Figure 20, no attempt is made to pursue a solution to the energy balance, but instead, the energy balance is used to identify the governing variables. Empirical data are then generated using a numerical experiment, where the identified variables are manipulated, and the data are analysed using a multiple linear regression analysis in order to find a correlation (Equation 13) that fits the data. Consequently, an inductive approach, i.e. a theory is constructed based on empirical data (Andersson 2012, p. 15), is applied. A correlation is a measure of the relation between two or more variables (see Section 4.2.3). Even so, a correlation can arise due to coincidence or to some confounding variable, which means that a correlation does not mean that there is a causal relationship between variables. However, in this case, the simplified energy balance is used to identify the independent variables, and in that sense, the first approach should not solely be regarded as "black box testing" (see Chapter 4) even though the resulting correlation can cause a "black box effect" because it includes constants with limited physical meaning.

The simplified energy balance is refined in the second approach, the lower branch in Figure 20, with the help of other supporting models such as the relationship between the hot-gas-layer interface height and opening mass flow (Equation 11a) that is presented in Paper III. These supporting models make is possible to solve the energy balance without using empirical data directly. By commencing from the simplified energy balance and using different supporting models without compensating, which can be done by adding constants with limited physical meaning, the resulting method will be transparent and flexible. Nevertheless, the estimations and simplifications made along the way may affect the validity of the final method negatively. The experimental work done in Paper V with regard to the second approach is considered to be a deductive study, i.e. predictions are made based on a theoretically derived relationship (Andersson 2012, p. 15). It also

resembles what Andersson (2012) refers to as "testing hypotheses by experiments" (see Chapter 4).

Both approaches have their strengths and weaknesses and it is not straightforward to determine which of the approaches that is preferable either for this specific case or in the more general sense of developing hand-calculation methods for fire safety engineering. It would, of course, be desirable to derive engineering models from some fundamental relations, but that is seldom possible in fire science. Therefore, experiments, both in form of traditional experiments and numerical experiments, are a successful research method in fire science.

There is no clear distinction between using empirical data and theoretical relationships and the two approaches in Figure 20 can be combined. This is illustrated in another paper by the author (Johansson, Wahlqvist and van Hees 2014) that is not included in the thesis. In the paper, two constants in a simplified ceiling jet theory were determined with the help of data from a numerical experiment; consequently, both a theory and empirical data were needed in order to present a model.

RQ3: How can the hot-gas-layer temperature and interface height in adjacent rooms be predicted with simple hand-calculation methods?

Two methods are presented in this thesis and the author worked on developing and validating them together with the co-authors of the appended papers. Method 1, which is developed in Paper IV, consists of a single empirical correlation (see Equation 13).

$$\Delta T_2 = 10.4 \frac{\dot{Q}^{0.73}(A_{O,1}\sqrt{H_{O,1}})^{0.24}}{A_{T,1}^{0.45} A_{T,2}^{0.33}(A_{O,2}\sqrt{H_{O,2}})^{0.19} h_k^{0.34}} \tag{13}$$

Method 2, which is presented in Paper V, is based on a mass and energy balance and it consists of several different steps and supporting models. The second method is more tiresome to apply, but at the same time, more transparent than Method 1. Method 2 is also more flexible because there might be alternatives to the different supporting models, e.g. different types of plume models, and in such a case, the most adequate supporting model for the problem should be used. Furthermore, Method 2 allows the possibility of taking into account the different enclosure materials in different rooms.

Method 2 includes in the following five steps.

1. The height to the hot-gas-layer interface in the first room, $z_{int,1}$, is calculated by using the following three equations.

$$\dot{m}_p = \dot{m}_g \tag{2}$$

$$\dot{m}_g = 0.684 A_o H_o^{1/2} (1 - z_{int,1}/H_o) \tag{11a}$$

$$\dot{m}_p = 0.0058 \dot{Q}_c (z/L) \tag{16}$$

2. When $z_{int,1}$ is known from step 1, it is possible to calculate $\dot{m}_g$ using Equation 11a.

3. Since no mass disappears in the compartment, $\dot{m}_g$ at opening B will be the same as at opening A (see Figure 15) and the hot-gas-layer interface height in the adjacent room, $z_{int,2}$, can be calculated using Equation 11a.

4. The temperature increase in the room of fire origin can now be calculated using a simple energy balance (Equation 17), where the heat losses due to convective flow thorough the opening and heat transfer to the boundaries are accounted for.

$$\Delta T_1 = \frac{\dot{Q}_c}{(\dot{m}_g c_p + h A_{w,1})} \tag{17}$$

5. Finally, it is possible to solve the energy balance (see Equation 14) and to calculate the excess temperature in the adjacent room.

$$\Delta T_2 = \frac{\dot{m}_g c_p \Delta T_1}{\dot{m}_g c_p + h A_{w,2}} \tag{18}$$

Both Method 1 and Method 2 are applicable for rather simple two-room geometries. Even so, they are believed to illustrate which variables will be of importance in a multi-room geometry. Method 2 can also be applied for more complex situations, and in Annex B it is demonstrated on a three-room compartment.

RQ4: In what order of magnitude are the uncertainties that are associated with the presented hand-calculation methods?

Models are, by definition, a simplification of reality and this means that a model will give a prediction of a certain phenomenon with a certain accuracy, e.g. there will be some uncertainty associated with the model.

The uncertainties of the two methods presented in the previous pages were assessed in Paper V with regard to one small-scale experiment that included 52 tests. The estimated model uncertainty is dependent on the experimental uncertainty, and if the experimental uncertainty is overestimated, it means that the model uncertainty is underestimated. The model bias and precision presented in Paper V are summarised in Table 5 and Table 6.

Table 5: Model bias (β) and precision ($\tilde{\sigma}_M$) in calculations of hot-gas-layer temperature. The MQH correlation (Equation 3) is included for reference.

Method	Location	β	$\tilde{\sigma}_M$
MQH	Fire room	1.04	0.08
Method 1	Adjacent room	0.90	0.12
Method 2	Fire room	0.73	0.10
Method 2	Adjacent room	0.75 (0.73*)	0.14 (0.13*)

* Outliers excluded

Based on Table 5, it is clear that the bias is closer to 1 in Method 1 than in Method 2. As previously described, Method 2 does include several simplifications while Method 1 provides a best-fit to empirical data within a certain range. The constants provided by the best-fit analysis will compensate for the simplifications inherent in the energy balance, and this is probably the reason why Method 1 gives a better agreement.

The precision of the two methods is similar. However, there is an indication that the precision is poorer in the adjacent room. This is reasonable because the complexity increases when the conditions in adjacent rooms are studied. The temperature in the adjacent room is dependent on factors in the adjacent room, but of course, also on the conditions in the first room. The precision in term of absolute temperature might, however, not differ between the rooms because the temperature in the adjacent room will be lower than in the first room.

Table 6: Model bias and precision in calculations of height to the hot-gas-layer interface with Method 2.

Location	β	$\tilde{\sigma}_M$
Fire room	1.04	0.07
Adjacent room	0.94 (0.99*)	0.21 (0.12*)

* Outliers excluded

The model bias and precision in the hot-gas-layer interface height calculations with Method 2 (see Table 6) will be better than for the temperature predictions. This is reasonable because the hot-gas-layer interface height is calculated as a step in Method 2 when the hot-gas-layer temperature is calculated. The precision, as for the hot-gas-layer temperature calculations, will be worse in the adjacent room. A probable reason for this is that Equation 18 was developed for a single room with an opening to the outside and not for calculating the gas flow between two connected rooms. Furthermore, the equation is optimized for temperatures above 200°C and the temperatures in the adjacent room were slightly lower in the small-scale experiment.

5.3 Addressing the research objective

The topic of this thesis is to explore the area of multi-room compartment fires. Papers I, IV and V directly contribute to a better understanding of the area in several aspects. Paper II does not have a direct link to the topic but is a prerequisite for being able to address RQ2, which in turn makes it possible to develop the correlation presented in Paper IV. Paper III deals with a single-room compartment but the simplified expressions presented in the paper are used and evaluated in Paper V.

The overall objective of the thesis includes developing new validated hand-calculation methods that can be used to study conditions outside the room of fire origin in pre-flashover fires. Papers IV and V are especially devoted to answering this overall objective, and two hand-calculation methods are developed and evaluated in these two papers. These methods can be used to calculate hot-gas-layer interface heights and temperatures, which are considered to be the most used criteria for assessing hazardous conditions in fire safety engineering. The two methods work in different ways, but both can be applied to provide an understanding of the conditions in a multi-room compartment fire.

6 Discussion

This thesis works in the paradigm of the compartment fire and this means that the work conducted only covers a part of all possible fires in buildings. Several others have previously explored compartment fire phenomena, and that previous research has formed the basis for this thesis. The focus on multi-room compartment fires in this thesis is motivated by the lack of simple hand-calculation methods for such events. Fire is a complex phenomenon and simple and transparent methods are therefore important in many aspects. Firstly, such methods can aid the understanding of fire dynamics in multi-room compartment fires by engineers, researchers and other people active in the field of fire science. To have a fundamental understanding of the relevant phenomena is considered to be very important in order to execute advanced calculations methods and models correctly. Secondly, simple methods can be used in an initial stage of fire safety design in order to determine if more detailed analyses are needed. Simple methods can also be used in probabilistic designs, e.g. in Monte Carlo simulations where hundreds of calculations might be needed. Finally, simple methods can be used in parametrical studies to increase the knowledge of what factors will determine the conditions in a multi-room compartment.

The derived models, the research results and the applied scientific methodologies in this thesis are discussed in this chapter.

6.1 Derived models

Two different methods that can be used to calculate hot-gas-layer temperatures in two-room compartments are presented and evaluated in this thesis. The first method provides better predictions compared to the second method in the evaluation presented in Paper V. The models included in the methods are based on the same simple energy balance (Equation 5); however, the simplifications in the energy balance (discussed in Section 3.2) have different impacts on the two methods. In Method 1, the phenomena that are not described in the variables included in Equation 13 are compensated for with empirical constants. This is probable the reason why Method 1 gives better predictions than Method 2 in the adjacent room. Method 2 is based on a deductive approach and no compensations are made for the simplifications inherent in the energy balance used.

Subsequently, Method 1 gives better predictions of the experimental tests in Paper V, but with the disadvantage that a "black box effect" is introduced and that the method should not be applied for circumstances other than cases similar to the observations it is based on.

The first method is easy to use and does not demand much of the user, except for providing the input. The second method consists of several calculation steps that make the procedure a bit more tiresome. However, there are advantages to the second method. Firstly, the method is considered to be transparent because it is based on energy and mass balances and these are solved with a calculation procedure that is divided into different steps. Consequently, the user will have a good opportunity to understand the fundamental physics behind the problem and the "black-box effect" will be limited. Secondly, the method is more flexible than Method 1 because it is possible to use alternative supporting models and different enclosure materials in different rooms. Finally, Method 2 will give more than the hot-gas-layer temperature because the interface height, as well as the mass flow, will be produced as a result of the calculation; this makes the method resemble a simple multi-room two-zone model.

The models included in the two methods used to calculate adjacent room temperatures have not been compared to experimental data to the extent done in Paper V previously. The MQH-correlation (Equation 3), which is constructed in a similar manner to the correlation in Paper IV, has been compared to experimental data in several previous publications. In a study by NIST (Overholt 2014) the MQH-correlation was evaluated against 78 data points from 5 data sets and the bias and the relative expanded uncertainty of the correlation were calculated to be 1.17 and 14% (i.e. $\tilde{\sigma}_M$=0.07), respectively. The higher bias compared to that in Paper V (see Table 5) is probably due to the larger amount of data sets and the fact that the experiments had been performed by many different organizations. The precision, $(\tilde{\sigma}_M)$, is however similar to what is estimated for the fire room in Paper V. In Paper V, the same people performed all the experimental tests and the calculations, and all the data points originate from one data set.

6.2 Reflecting on validity and reliability

This thesis is considered to contain several novel contributions that are related to the four research questions addressed in Section 5.2. In this section, the internal validity, external validity and reliability of the research results are reflected upon.

6.2.1 External validity

The presented models for calculating temperatures in adjacent rooms are based on the concept of the compartment fire and this will limit the possible uses of the models. The compartment fire concept is well established in fire science, but it is not a universal model. How a fire develops in a building will depend on the layout of the building, where the fire starts and how it will spread. Figure 4 gives a simple illustration of different categories of fires in buildings. There will also be different stages of fire development and there is obviously no general model that applies to all circumstances. Consequently, it is not useful to discuss the external validity of the developed models outside their recognised limitations.

The models that were derived in this thesis work are kept simple, but a too-high degree of simplification might result in threats to the external validity. There is consequently a balance between keeping a calculation method simple and transparent, and including enough to keep the external validity at a reasonable level. In the case of the hand-calculation methods presented in this thesis, more details could be added, but at the expense of the methods becoming more complex. An increased degree of complexity might not be rational with regard to the uncertainties of the fire phenomena. This is because even if a fire situation is rather well specified, there will be other factors that can affect the outcome and this will introduce a variation in results, as illustrated in Paper I. In the light of the degree of variation presented in Paper I and the principle of parsimony, it is not considered worthwhile to increase the complexity of the derived methods to gain a slight increase in precision.

The correlation to calculate adjacent room temperatures in Method 1 is based on empirical data from a numerical experiment with FDS. It is consequently based on data from a numerical model and a prerequisite for doing that, according to Paper II, is that the numerical model must have been validated for the relevant circumstances. That is considered to be the case with regard to Equation 13 because the relevant physical parameters (as presented by McGrattan, Peacock and Overholt (2014), i.e. the fire Froude number, flame height relative to ceiling height, global equivalence ratio and compartment aspect ratios) in the numerical experiment are comparable to the experiments used in relevant validation studies of FDS.

In Paper V, the validity of the two methods was studied by comparing them to several small-scale tests. The small-scale tests constitute a simple and rather controlled case, and there will be other influencing variables in a real fire situation that were not accounted for in the tests or that are regarded in the two methods. The fire size was constant in all tests, but in a real fire situation the fire will most likely grow with a speed that is dependent on, e.g., the type of fuel and enclosure

characteristics. The fire was placed in the centre of a room, which is also an idealised situation. These types of idealisations are however considered to be necessary in order to derive models that address the purpose of providing good and transparent hand-calculation methods for multi-room compartment fires.

The derived model bias in Paper V can, with the limitations of the small-scale experiment in mind (see discussion in Section 6.3.1), be seen as a measure of the external validity of the models. The model bias and precision gives a description of the uncertainty and, consequently, the accuracy of the models. The models included in the first method will have a better external validity when it comes to predicting hot-gas-layer temperatures. The second method includes a model for calculating the hot-gas-layer interface height and this model shows a lower uncertainty, compared to the calculations of the hot-gas-layer temperature in Method 2. This is reasonable because it constitutes a step in the calculation procedure of the hot-gas-layer temperature. However, Equation 18, which is fundamental for estimating the hot-gas-layer interface height, is developed for a single room with an opening to an open ambient space. So, in cases when the flow through the adjacent room is restricted (e.g. the opening in adjacent room to the next space is much smaller than the first opening) the accuracy of the prediction can be affected.

The accuracy of the hot-gas-layer temperature prediction in Method 2 might have been increased if more than only the convective part of the HRR had been accounted for when calculating the hot-gas-layer temperature. Annex A includes a suggestion for a rough method to estimate the radiative part of the HRR. Another issue that can have an effect on the accuracy of Method 2 is that no account is taken of the fact that the two rooms have a common wall. The heat transfer through the common wall will be different compared to the other surfaces in contact with hot gases because the temperature difference over the wall will be different.

As an answer to RQ2, two different approaches are presented in Figure 20 that are used in the thesis to derive methods for calculating temperatures in adjacent rooms. There are other possibilities for collecting data, e.g. full-scale or small-scale experiments, but Figure 20 is considered to cover the two fundamental approaches that are available, an empirical approach and a theoretical approach.

So far, only the external validity of the two models has been discussed, but the external validity of the work presented in Paper I should also be mentioned. Although Table 4 provides some answers to RQ1, it is apparent that there is no single answer to RQ1, because such an answer would be dependent on many factors. The observational study in Paper I included one single experimental setup with unique characteristics. There are many other factors that can affect the

generalizability that were not considered in Paper I, e.g. the size and position of the fire, thermal properties of the boundaries and the density of measurement equipment coverage. Furthermore, only the temperature variation was studied in Paper I.

The temperature will, as previously mentioned, have a great impact on the conditions in a room, and temperature measurements with thermocouples are considered to be the most common measurement in fire experiments. It is therefore considered to be the most interesting property to study with regard to RQ1. The HRR used in the experiment in Paper I is not unreasonable in a pre-flashover situation, and it is probably in the range of what would be used in a compartment fire experiment of this kind. For example, Peacock, Davis and Lee (1988) and Nakaya et al. (1986) used fires with HRR of a similar order of magnitude in multi-room compartment fire experiments. The size of the three-room apartment in Paper I is small compared to the typical Swedish apartment (Boverket 2011, p. 14), but it is still in the range of what can be expected to be used in experimental tests. The lightweight concrete and concrete used in the structure are also considered to be representative of materials used in an apartment building.

The ventilation conditions in multi-room compartment fire experiments will, of course, also vary. This issue was addressed to some extent with the four different ventilation scenarios studied in Paper I. The ventilation scenarios made it possible to see that the variation will be greater when the ventilation is limited. It was also seen in Paper I that the degree of variation changed between the growth phase and the steady-burning period of the fire, and in general, the variation during the growth phase was greater than during the steady phase.

6.2.2 Internal validity

The internal validity refers to the extent to which it can be said that the results describe a causal relationship. There will always be some degree of uncertainty in results and therefore it will never be possible to prove causation (Andersson 2012, p. 88).

The second method is based on a deductive research approach. First, a theory was established and later tested on observations from experiments. The simplified model for door mass flow derived in Paper III that is used in Method 2 was also derived with a similar approach. Models derived in this manner are considered to hold a high level of internal validity and it is not by coincidence that Method 2 gives reasonable predictions when compared to experimental data in Paper V.

The first method, which is based on an empirical correlation, is however not as easy to promote on the grounds of having a high internal validity. A regression

analysis was used to derive the correlation and it cannot be ruled out that there are confounding variables involved when using such an approach. The independent variables were, however, chosen on the basis of a simple energy balance consisting of the most important variables. Therefore, it is rather certain that it is not by chance that the correlation in Method 1 provides good predictions of the experiment conducted in Paper V.

Internal validity can also be discussed with regard to the work presented in Paper I. However, it was not the purpose of the paper to determine what causes the variation between the reproduced tests. It was mentioned in the paper that the variation in the results were probably due to the variations in the weather conditions and other unknown factors, but no correlation between these and the variation could be found when the data were studied.

6.2.3 Reliability

The reliability of the methods in this work can be described with the precision derived in Paper V. As stated in Paper V, it is not possible to show that a model is more accurate than the experiments it is compared to; subsequently, it is not possible to demonstrate the model uncertainty to be less than the experimental uncertainty. Therefore, the model uncertainty presented in Paper V will be dependent on the experimental uncertainty and if the predictions had been made with regard to another experiment, the model uncertainties would have been different. This means that it is not possible to generalise on the presented values of the bias and precision in Paper V. Even so, the performed experiment is considered to represent typical compartment fires for which the two methods are intended, and hence, the stated values of the precision (see Table 5 and Table 6) can be seen as reasonable approximates of the reliability.

The reliability with regard to the results of Paper I can be discussed in the sense of how reliable the resulting variation is for the different scenarios. A total of 45 different fire tests were studied in Paper I and these were divided between four different scenarios. This meant that between 8 and 15 fire tests were performed for each scenario. This is considered to be a large number of tests compared to the usual number of replicate tests in experimental studies and standardised fire tests, for instance, in the single burning item test (EN 13823 2002) it is prescribed that three specimens should be tested. Adding additional tests in the study in Paper I is not believed to influence the resulting variation much.

Paper II includes a review and qualitative analysis of numerical experiments in fire science. The paper is exploratory and it is difficult to discuss the reliability of the conducted analysis. However, the analysis and discussion is considered to be

transparent and nuanced in order to give the readers the opportunity to form their own opinion of how numerical experiments can be applied in fire science.

6.3 Reflecting on the applied methods

The research methods used in the thesis will influence the results, so in this section, the applied data collection and data analysis methods are reflected upon and the suitability of the methods with regard to the conducted research is discussed.

6.3.1 Data collection methods

The full-scale test data that were used in Paper I were collected for a different purpose than what it was used for in Paper I. Therefore, the study cannot be considered as an experimental study, as described in Section 4.1, due to the inability to systematically manipulate different variables. Instead, it should be regarded as an observational study, and this limits the type of relationships and knowledge that can be derived (see Figure 9). If it had been possible to perform a more active manipulation of the tests, it would have been a completely different study, and it could have been possible to better describe which variables influenced the variation. Still, the work is considered important and it provides valuable information on the size of the variation that can be expected in a certain fire situation. The next step would be to perform similar studies but with a higher level of control in order to see how much other factors, e.g. wind speed, would influence the reproducibility or repeatability of an experiment.

The small-scale arrangement used in Paper V made it possible to use the available laboratory facilities and to maintain a high level of control of the experiment. It is, as mentioned in Section 4.1.2.2, not possible to perform complete scaling of compartment fire experiments, and in the case of Paper V is radiation not scaled correctly. This might have influenced the results when heptane was used as fuel, because, heating of the container and the fuel surface due to radiation can affect the mass loss rate and subsequently also the HRR. However, similar types of relationships between the HRR and temperature were observed for both heptane and methane in the small-scale experiment, and in the case of methane the fuel mass flow was controlled. Furthermore, in the experiment, several important physical parameters (e.g. fire Froude number and compartment aspect ratios) were kept at the same order of magnitude, as they would have been if a traditional full-scale experiment had been conducted. Consequently, the result of the evaluation of the two methods in Paper V would probably be similar if a full-scale experiment had been used instead of the performed small-scale experiment.

In order to review the quality of the model predictions in Paper V, it was necessary to have an idea of the experimental uncertainty in the experiment. The measurement uncertainty in the thermocouples was estimated based on previously published data and the uncertainty in the position of the thermocouples was based on estimations. Furthermore, uncertainties in the HRR and thermal conductivity were included in the propagated input uncertainty. However, there are several factors that have not been accounted for: no compensation for radiation effects on thermocouples was made in the assessment of the measurement uncertainty; the HRR and thermal conductivity were assumed to be uncorrelated; and no account was taken to that the thermal properties of the experimental rig could have changed due to heating and cooling between tests. Still, the resulting experimental uncertainty was comparable to that in similar types of experiments (McGrattan, Peacock and Overholt 2014) and, as discussed in Paper V, it is not believed that the mentioned factors would have influenced the experimental uncertainty to any large degree.

Data were collected in Paper IV with the help of a numerical experiment. Numerical experiment as a research method in fire science is discussed thoroughly in Paper II and several aspects of using numerical experiments were presented in Section 5.1.2 in this thesis. With regard to the study in Paper IV, it was not a reasonable option to perform the same number of traditional experimental tests, nor was it an option to reduce the number of tests because a large number of observations were needed to perform a satisfactory regression analysis. Even performing the same number of observations in small-scale was not considered possible. Consequently, a numerical experiment was considered to be the most reasonable data collection method to use for the study.

Other experimental approaches could have been applied in the conducted research, but considering the available resources, it is considered that the most efficient research methods were applied for addressing the research questions. Furthermore, it is not believed that the choice of experimental method affected the outcome of the experimental studies presented in this thesis to any critical degree.

Apart from the observational and experimental studies performed, reviews of scientific publications and theoretical relationships were conducted in Paper II and III, respectively. The review in Paper II was conducted on mainly peer-reviewed publications, but the interpretations by the author are qualitatively and subjective; however, it is not believed possible to perform this type of exploratory study without some degree of subjectivity. The review of the theoretical relationship in Paper III involves providing numerical solutions of the equations in order to collect data that can be used to derive an approximate simplified expression. This

approach is quantitative and does not involve the same amount of subjectivity as in paper II.

6.3.2   Data analysis methods

Descriptive statistics were used in Papers I and V in order to analyse data. The mean and standard deviation are well-known measures with fairly easy-to-interpret meanings. These measures are, however, not possible to be used when comparing two sets of data, e.g. two time-temperatures curves, which was done using functional analysis in Paper I. The three measures (ERD, EPC and SC) used in the functional analysis to compare data sets are more difficult to grasp, but they provide a powerful toolbox when two data sets are compared. The normal use of functional analysis in fire science is to compare experimental data with model predictions. In Paper I, the averages of the data sets were compared to each individual data set for each scenario. This meant that the three measures gave a representation of the variation. Functional analysis, as well as descriptive statistics, provides quantified measures that describe the data from, e.g., an experiment, but these values need to be interpreted in order to be valuable for a study. In Papers III, IV and V, model predictions are compared to data from experiments or simulations using descriptive statistics and qualitative assessments. The models in these papers are applicable for steady-state situations and it is not relevant to use functional analysis as in Paper I, where transient conditions are studied.

Regression analysis was used in Paper IV. Regression analysis of empirical data is a common approach in fire science in order to derive mathematical expressions for some phenomena. As previously mentioned, it is possible for a "black box effect" to be created when such an approach is applied. This is a drawback of regression analyses as well as the fact that it can be hard to rule out the existence of confounding variables. In the case of the correlation presented in Paper IV are the effects of confounding variables considered to be limited because the correlation is based on an energy balance in which the most important variables are identified and physically justified. It is not likely that there are other variables that will have a large influence on the hot-gas-layer temperature.

Model predictions have been compared to experimental data in Papers III and IV and the evaluation has been made qualitatively. When this type of subjective and qualitative analyses were applied have also the relevant data been presented in tables of graphs to allow the reader to make an own interpretation. It is considered to be a prerequisite for this type of qualitative analysis to present the data that the analysis is based on.

7 Conclusions

The topic of the thesis was to explore the area of multi-room compartment fires with the objective of developing new simple and validated hand-calculation methods for studying conditions in rooms adjacent to the room of fire origin. The research in the papers is combined into a unit in this thesis in order to address this objective. The thesis contains several novel contributions that are considered to be valuable both for the practicing fire safety engineers and researchers in the field of fire science. The major contributions of the thesis are listed below:

- The reproducibility of a typical full-scale apartment fire experiment will be on the order of ± 10-35%. The reproducibility will be dependent on the ventilation conditions; it will be easier to reproduce a well ventilated scenario. The placement of measurement equipment and the time after ignition will also affect the reproducibility.

- Numerical experimentation is a promising research method in fire science. It holds both advantages and drawbacks compared to traditional experiments. However, no experimental method can be recommended for all circumstances; therefore, different experimental methods, such as numerical experiments and traditional full-scale experiments, should be seen as complementary rather than competitive.

- Simple models and methods that can be used to better understand a problem are important and especially valuable in fire science, which deals with complex phenomena. Two such methods for calculating conditions in an adjacent room, have been presented in this thesis. The methods are based on the same simple energy balance and the compartment fire concept, but they have been derived differently. The first method consists of a single mathematical expression that was shown to predict the hot-gas-layer temperature in an adjacent room within 10% of experimental values. The second method consists of several calculation steps, but is more transparent and it was shown to predict both the hot-gas-layer height and temperature in an adjacent room to within 5 and 30%, respectively, of experimental values.

- The presented hand-calculation methods are a valuable contribution to the fire engineer's toolbox. The methods can be used to quickly make estimate calculations in fire safety designs and evaluations. This type of simple methods can also be used to conduct fire risk analyses. Furthermore, the methods can be used to understand which variables that are of importance in complex fire dynamics problems, such understanding is considered essential for the execution of advanced computer models.

8 Future research

The work in this thesis is considered to provide a valuable contribution to the area of multi-room compartment fires. There are, however, several areas within, or related to, the topic of this thesis that need attention in the future.

The methods presented and analysed in this thesis can be evaluated and also developed further. The two methods presented are evaluated with a small-scale experiment in Paper V, but further evaluation with data from full-scale experiments is desirable. Furthermore, the two methods are only valid for a simple well ventilated case with the fuel placed in the centre of the inner room, and future work could be performed in order to develop and refine the including models to make the methods applicable for other situations.

The thesis highlights the importance of having simple methods, in parallel with advanced computer models, in order to gain a conceptual understanding of the fire dynamics of the studied problem. Such methods are considered to be valuable for not only compartment fires, but also for other types of fires in buildings. It has been argued that the compartment fire model is insufficient when it comes to describing fires in large enclosures (Torero et al. 2014). Similar approaches as those used in this thesis could be applied for creating simple engineering methods for fires in large enclosures. Fires in structural elements are another type of building fires, as described in Figure 4, and it is a rather unexplored area. It is believed to be difficult to construct simple hand-calculation methods for fires in structural elements. Nonetheless, it is an area that needs more attention in the future because it is very important to understand how fire spreads and develops in structural elements such as walls, attics and facades in order to decrease property losses.

The reproducibility and also the repeatability of full-scale compartment fire experiments can be explored further. A next step would be to perform similar studies as those in Paper I, but with a higher level of control in order to see how factors such as wind speed will influence the reproducibility or repeatability of an experiment. It would also be desirable to study the reproducibility of quantities other than temperature that are of importance in fire safety engineering, e.g. heat flux and optical density.

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Annex A

Radiation in pre-flashover compartment fires

In this annex, the radiation in compartment fires is studied by performing two approximate calculations. The first calculation is performed in order to estimate the portion of the radiative loss from a hot-gas-layer through an opening in a single-room compartment fire. The second calculation is performed to estimate the contribution of the radiative part of the total heat release rate (HRR) to the hot-gas-layer in a pre-flashover fire.

A.1 Radiative loss from a hot-gas-layer through an opening

In Section 3.1, an energy balance is presented and it is argued that the radiative loss from a hot-gas-layer through an opening is small with regard to the total HRR. An estimate of the radiative loss is done in this section.

The radiative losses from the hot-gas-layer in a pre-flashover fire through an opening ($\dot{Q}_R$ in Equation 1, Section 3.1) can be approximated for a single room using the following expression.

$$\dot{Q}_R = A_o(1 - \frac{z_{int}}{H_o})\mathcal{E}\sigma(T_g^4 - T_a^4) \tag{A.1}$$

A room with dimensions as a standard ISO 9705 (2001) room, i.e. a room with the dimensions $3.6 \times 2.4 \times 2.4$ m and a 0.8×2.0 m opening, is used to quantify $\dot{Q}_R$. The room is made of 0.2 m thick concrete (see Table A.1). A 300 kW fire with a radiative fraction (χ_r) of 0.35 in the room will result in a temperature increase of 134 K and interface height of 1.34 m after 300 seconds according to Method 2 (presented on page 51). If the emissivity is assumed to be 1, it will result in $\dot{Q}_R$=0.8 kW. The relationship between $\dot{Q}_R/\dot{Q}$ and the variables included in Equation A.1 is illustrated in Figure A.1.

Density, ρ	2100 kg/m³
Specific heat, c	880 J/kg K
Thermal conductivity, k	1.1 W/m K

Table A.1: Thermal properties of concrete, the values are from Table 6.1 in Karlsson and Quintiere (1999).
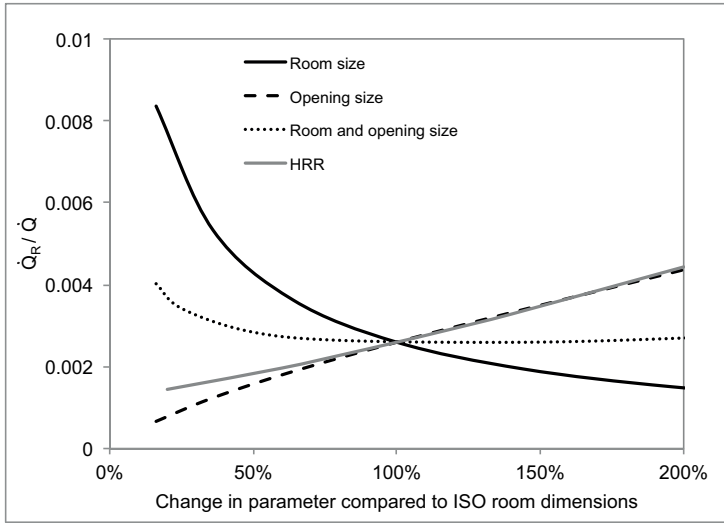
Figure A.1: The relationship between $\dot{Q}_R/\dot{Q}$ and variables included in Equation A.1.

It is obvious when studying Figure A.1 that $\dot{Q}_R$ will constitute only a small part of the total HRR. It is also clear that the room size and HRR will have a large influence on $\dot{Q}_R$ because both these variables will influence the gas temperature, on which $\dot{Q}_R$ is strongly dependent.

A.2 Contribution of the radiative fraction to the hot-gas-layer

In Paper V, only the convective part of the HRR is assumed to heat the hot-gas-layer. This is a simplification that will probably yield an underestimation of the hot-gas-layer temperature. An approximate calculation is performed in this section to attempt to quantify the part of the radiative fraction that contributes to the heating of the hot-gas-layer.

If it is assumed that the radiative part of the HRR is distributed evenly in the room, the radiative energy will reach the hot-gas-layer, the floor and walls beneath the hot-gas-layer, and leave the room through openings (as estimated in Section A.1). If the room is cubical, the radiative energy that will heat the hot-gas-layer ($\dot{Q}_{r,HGL}$) will be proportional to the radiative part of the HRR ($\chi_r\dot{Q}$) and z_{int}/H. With these assumptions, the following expression can be used to approximate $\dot{Q}_{r,HGL}$.

$$\dot{Q}_{r,HGL} = \chi_r\dot{Q}\left(1 - \frac{A_o}{A_T}\right)\left(1 - \frac{z_{int}}{H}\right) \qquad (A.2)$$

The equations in Method 2 (presented on page 51) and Equation A.2 can be used to quantify $\dot{Q}_{r,HGL}$ for a standard ISO 9705 (2001) room made of 0.2 m thick concrete (see Table A.1). A 300 kW fire with a radiative fraction of 0.35 will yield an interface height of 1.34 m after 300 seconds it results in a $\dot{Q}_{r,HGL}$ of 45 kW (15% of $\dot{Q}$) according to Equation A.2. The results of a variable analysis of Equation A.2 are presented in Figure A.2.
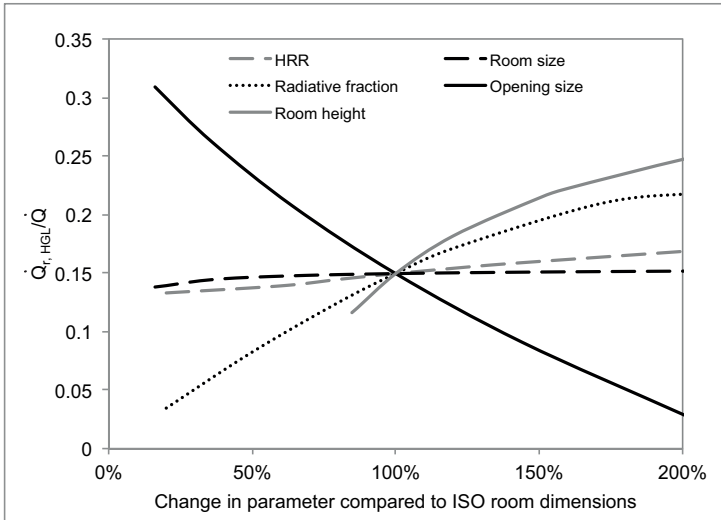

Figure A.2: The relationship between $\dot{Q}_R/\dot{Q}$ and variables included in Equation A.2.

Equation A.2 is not straightforward to interpret because z_{int} and several of the variables in Equation A.2 are interdependent. The interface height is strongly dependent on the size of the opening according to Method 2 and consequently, $\dot{Q}_{r,HGL}$ will be strongly dependent on the opening size.

Equation A.2 is a simple and general model. For instance, the radiative heat losses from the hot-gas-layer through the door opening and to the lower layer are ignored. However, Figure A.2 is considered to reveal the order of magnitude of $\dot{Q}_{r,HGL}$ for a typical pre-flashover fire, and it is obviously possible to complement and refine Method 2 further by accounting for $\dot{Q}_{r,HGL}$.

Annex B

Example calculation in a three-room apartment

This annex is devoted to demonstrating how Method 2, described in Paper V and Section 5.1.5, can be used to calculate the temperature in a three-room apartment. The calculated temperatures and interface heights in the three rooms are compared to predictions using the two-zone model CFAST (Peacock, Forney and Reneke 2012).

B.1 Problem description

A simplification of the compartment geometry used in the test setup in Paper I (see Section 5.1.1) is used to demonstrate Method 2. The main simplifications made are the following: the stairwell is neglected, the positions of the openings are changed (see Figure B.1), and the sizes of the openings are modified.
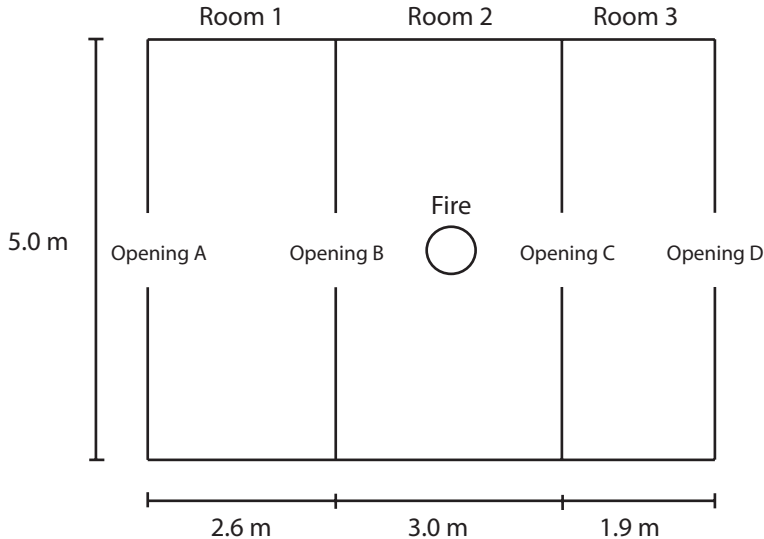

Figure B.1: Layout of the three-room apartment.

All openings are assumed to be 0.9 m wide and 2.0 m high and the ceiling height is assumed to be 2.4 m. The compartment boundaries are constructed of 0.15 m

thick lightweight concrete. The thermal properties of the material are taken as the default values in the CFAST material database (see Table B.1).

Density, ρ	525 kg/m³
Specific heat, c	1050 J/kg K
Thermal conductivity, k	0.125 W/m K

Table B.1: Thermal properties of lightweight concrete from the CFAST database.

The fire has a diameter of 800 mm and the HRR is 800 kW. The radiative fraction is 0.35.

B.2 Solution

The calculation procedure is performed in several steps. Firstly, it is assumed that $\dot{m}_p = \dot{m}_g$ and the height to the hot-gas-layer interface in the fire room (Room 2), $z_{int,2}$, can be calculated with the following equations.

$$\dot{m}_g = 0.68 A_{o,2} H_o^{1/2} (1 - z_{int,2}/H_o) \tag{B.1}$$

$$\dot{m}_p = 0.0058 \dot{Q}_c (z/L) \qquad \text{valid for } L > z_{int,2} \tag{B.2}$$

This will result in the following expression:

$$0.0058 \dot{Q}_c (z_{int,2}/L) = 0.68 A_{o,2} H_o^{1/2} (1 - z_{int,2}/H_o) \tag{B.3}$$

where $A_{o,2} = A_{o,B} + A_{o,C}$ and $H_o = H_{o,B} = H_{o,C}$. The flame height, L, is calculated with Heskestad's flame height correlation:

$$L = 0.235 \dot{Q}^{2/5} - 1.02 D_f = 2.6 \, m \tag{B.4}$$

All variables except $z_{int,2}$ in Equation B.3 are known; subsequently, $z_{int,2}$ is possible to calculate to 1.20 m. Since the openings B and C are equally sized, then $\dot{m}_{g,B} = \dot{m}_{g,C} = 0.5 \dot{m}_g$. This means that the hot-gas-layer interface height in Room 1, $z_{int,1}$, and in Room 3, $z_{int,3}$, can be calculated using Equation B.1.

$$\dot{m}_{g,B} = \dot{m}_{g,A} = 0.68 A_{o,A} H_{o,A}^{1/2} (1 - z_{int,1}/H_{o,A})$$

$$\dot{m}_{g,C} = \dot{m}_{g,D} = 0.68 A_{o,D} H_{o,D}^{1/2} (1 - z_{int,3}/H_{o,D})$$

Opening A and D are equally sized, which means that $z_{int,1} = z_{int,3}$. The hot-gas-layer interface height in the adjacent rooms is calculated to 1.20 m. The temperature increase in the fire room can be calculated with Equation B.5.

$$\Delta T_{g,2} = \frac{\dot{Q}_c}{(\dot{m}_g c_p + h A_{W,2})} \tag{B.5}$$

The specific heat capacity, c_p, is assumed to be 1 kJ/kg K and the area of the boundaries in contact with the hot gases, $A_{W,2}$, is calculated as follows:

$$A_{W,2} = (l_2 \cdot w_2) + 2 \cdot \left(l_2 \cdot (H_2 - z_{int,2})\right) + 2 \cdot \left(w_2 \cdot (H_2 - z_{int,2})\right)$$
$$- \left(w_{o,B} \cdot (H_{o,B} - z_{int,2})\right) - \left(w_{o,C} \cdot (H_{o,C} - z_{int,2})\right)$$

The heat transfer coefficient, h, to the surfaces in contact with the hot-gas-layer is not trivial to estimate. Equation B.6 can be used to calculate the heat transfer coefficient if it is assumed that the boundaries are semi-infinite and that the surface temperatures are the same as the gas temperature.

$$h = \sqrt{\frac{k\rho c}{\pi t}} \tag{B.6}$$

An alternative could be to use an empirically determined value of the heat transfer coefficient, but Equation B.6 is considered suitable for use in this example. The temperature increase in the fire room after 300 seconds will be 311 K according to Equation B.5. The hot-gas-layer temperature increase in Room 1 and Room 3 can be calculated using the following equations.

$$\Delta T_{g,1} = \frac{\dot{m}_{g,B} c_p \Delta T_2}{\dot{m}_{g,A} c_p + h A_{W,1}}$$

$$\Delta T_{g,3} = \frac{\dot{m}_{g,C} c_p \Delta T_2}{\dot{m}_{g,D} c_p + h A_{W,3}}$$

The area of the boundaries in contact with the hot gases in room 1 and room 3, $A_{w,1}$ and $A_{w,3}$, and the heat transfer coefficient can be calculated in the same manner as in the fire room. The hot-gas-layer temperature increase in Room 1 and Room 3 can be calculated to 227 and 254 K, respectively.

B.3 Comparison with CFAST predictions

A simulation was performed in CFAST in order to compare the results of the example in section B.2 to results from another calculation method.

CFAST is a two-zone computer fire model that is used to calculate the spread of smoke, fire gases and temperature throughout compartments consisting of several rooms. More information about CFAST can be found in the technical documentation (Peacock, Forney and Reneke 2011).

The input values with regard to the fire, compartment geometry and material properties as presented above were used in CFAST. The Heskestad plume model was selected to model the plume. All other possible inputs and options were left as

the default value. The results from the CFAST simulation and hand-calculations are presented in Table B.2.

	CFAST		Method 2	
	z_{int} (m)	ΔT (K)	z_{int} (m)	ΔT (K)
Room 1	1.20	212	1.20	227
Room 2 (Fire room)	0.97	332	1.20	311
Room 3	1.20	224	1.20	254

Table B.2: Results from CFAST simulations and hand-calculations with Method 2.

The predictions are quite similar for this specific case but it does not mean that similar results can be expected for other situations. It is therefore recommended that the hand-calculation method be used with care.

Annex C

Appended papers

Paper I Johansson, N., Svensson, S. and van Hees, P. (2014) "A study of reproducibility of a full-scale multi-room compartment fire," *Fire Technology*. DOI: 10.1007/s10694-014-0408-3.

Paper II Johansson, N. (2014) "Numerical experiments and compartment fires," *Fire Science Reviews,* 3(1). DOI: 10.1186/s40038-014-0002-2.

Paper III Johansson, N. and van Hees, P. (2014) "A simplified relation between hot layer height and opening mass flow," *Fire Safety Science*. [Published online]. Available at: http://www.iafss.org/publications fss/11/106/view (Accessed: February 18, 2015).

Paper IV Johansson, N. and van Hees, P. (2014) "A correlation for predicting smoke layer temperature in a room adjacent to a room involved in a pre-flashover fire," *Fire and Materials,* 38(2), pp. 182-193. DOI: 10.1002/fam.2172.

Paper V Johansson, N., Svensson, S. and van Hees, P. (2015) "An evaluation of two methods to predict temperatures in multi-room compartment fires," submitted to an international journal for peer review.