Usage of Lifts for the Evacuation of High-Rise Projects

An International Discussion from a Dutch Perspective

Final Thesis – February 19, 2010

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ABSTRACT

Vertical transportation of people and goods is one of the main focal points in high-rise buildings: as the average pedestrian doesn’t traverse more than six floors, a building’s lift system is the backbone of a high-rise building. During an emergency however, the traditional method of egress is via emergency stairwells, regardless of building height.

The conventional and well-known “In case of fire, use the stairs!” rule becomes increasingly difficult to remain a realistic solution as a building’s height increases: a human’s physical capabilities are limited, even without taking into account any added limitations due to age or physical disabilities. The concept of using lifts for evacuation started in the 1970’s and has been a topic of heated debates that were triggered by events like the Americans with Disabilities Act of 1990 and the 2001 terrorist attack of the World Trade Center in New York. In the highly competitive building industry where every square meter of lettable floor space counts, two fundamental interests keep clashing: economic feasibility and building safety.

From these debates, three basic questions can be distilled: what are the conditions to make evacuation using lifts viable, what is the best way to evacuate using lifts and how much time do we gain (or lose) when using lifts for evacuation? A major topic during these discussions is the effects of human behaviour and its influence on emergency egress in general and the use of lifts in particular. To this day, individual human behaviour is an abstract concept that remains difficult to capture in models.

The research conducted in this thesis provides solutions for these three basic questions, and it provides them from the perspective of the Dutch building industry. Building heights in the Netherlands are quite modest when compared to many other countries, and daylight requirements typically limit the population per floor. This causes the Dutch building industry to question the possible merit of the use of lifts for evacuation purposes. The trend of increasing heights and floor population densities for building projects is also visible in the Netherlands however, and the building industry emphasizes the increasing need for clear and unambiguous guidelines for high-rise buildings.

What are the conditions to make evacuation with the use of lifts viable?
Numerous international experts have provided answers to this question during the past four decades. The first condition mentioned is the need to separate all lift systems from the rest of the floor by compartmentation: by providing this extra layer of protection in combination with pressurization and/or dilution systems, the lift lobby, shaft, electronics and machine rooms are safe from smoke and hot gasses. The reliability of the lift system and the layers of protection are crucial: other important measures besides compartmentation are the ‘hardening’ of these systems and adding backup systems like emergency generators. The placement of at least one emergency stairwell directly next to the lift lobby is crucial as well: the direct proximity of the two means of egress allows for an integrated system with many advantages.

Besides the physical conditions much emphasis is laid upon the importance of the combination organisation – information – communication. Protocols made by the building officials need to be clear, simple and unambiguous, and they need to be known by and coincide with the protocols used by the emergency services. This can only be achieved by proper and regular communication between both parties and by regular joint evacuation drills. Building systems should provide easy-access information about the status of the building and its systems, so that building security and emergency services know what and where the problems are and if the evacuation system is safe to use. Important areas like rendezvous floors and skylobbies should be focal points for teams of Appointed Safety Supervisors (ASS) and the emergency services: here they can direct the evacuation process, keep the Fire Command Station informed of the local conditions and provide assistance for the evacuees.
Equally important is the information towards and communication with the building occupants. Information via monitors, two-way intercoms et cetera can be used to inform people what and where the problem is, what to do and where to go. Information appears to be one of the most important things that people need when an incident occurs: once they know what’s going on and where, evacuation delays will become shorter. The WTC disaster in particular shows that the risk of unforeseen situations due to panic or confusion is minimal as long as the information and directions are clear and the path of egress remains clearly visible and free of any signs of trouble (smoke, absence of power, congestion in the stairwells, obstructions). Figures of authority in important areas like rendezvous areas and skylobbies are reassuring and provide a source of information and, if necessary, assistance. Their decision making process on location will greatly benefit from a proper means of communication and information.

What is the best way to evacuate and how long does it take?
When regarding the combination of building height and population per floor, the calculations have yielded a clear result: in buildings with floor populations above 40 persons per floor and higher than 150 meters (assuming two emergency stairwells), evacuation using lifts starts yielding better results than evacuation by stairs only. The best method of evacuation in this case is to divide a building in two sections and design a rendezvous floor about halfway up. When an incident occurs, everybody enters the stairwell and starts their descent. The bottom half of the building population heads all the way down to the ground floor and exits the building; the top half heads down to the rendezvous area, where they exit the stairs and are received by an ASS team that is in charge of tending to the waiting people there and directing them into the lifts shuttling up to the rendezvous floor and back. Using this method, the evacuation time at the rendezvous floor stays relatively stable at between 10 – 12 minutes (for office buildings); the pedestrian egress times in the stairwells remain below 10 minutes and people don’t need to descend more than 15-20 floors. This means that rendezvous floors and, where applicable, skylobbies need to be designed as temporary refuge areas that are able to harbour a sufficient number of evacuees.

The method described above typically applies to office buildings; Residential buildings and hotels have lower populations per floor, making the method as described above counterproductive. In this case fractional evacuation is the best option: those people who aren’t able to use the stairs wait inside the protected lobby until are collected by the fire department, who use the (fire-fighter’s) lift to sweep the building, top to bottom.

Part of this thesis was dedicated to the question whether the traditional calculations used to determine pedestrian egress times could be altered to yield better, more nuanced results. While a number of simulation programs have been developed to do exactly this, the proposed method using factors has the advantage that no expensive computer programs are needed, making it suitable for guidelines or even building codes.

While the calculation results and the test cases gave mixed results, the overall conclusion is that the factors do indeed appear to give better results: the real life data marks more or less the area between the (linear) traditional calculation results and the results with added factors. This implies that the traditional calculation method becomes increasingly unreliable when the building height and population per floor increases: therefore it does pay off to limit the vertical distance that evacuees need to traverse (and thus the influence of age, fatigue, accidents et cetera) by using the stairs, for instance by transferring the population to the lift system.

With additional research using simulation programs, it should be possible to define these additional factors better and thus provide better results.
PREFACE

Fire Safety engineering is a fascinating subject: as a civil engineer, I found myself working with several other disciplines. Architects, fire department officials, Appointed Safety Supervisors and mechanical engineers are a few examples of the people that were involved in the research process. This provided a rich, multidisciplinary environment with many different ideas and perspectives about the concept of emergency egress using lifts.

The notion some people have that the building industry is a conservative field that cannot provide an atmosphere in which exciting research options and fast-paced developments are possible, has proven to be a false one. During the past eighteen months I've encountered numerous occasions where new developments, workshops and publications have influenced my own research profoundly. It was in fact often difficult to keep up with the continuous developments and steady stream of publications about evacuation from high-rise buildings, proving it to be one of the 'hot' topics in this field of expertise.

Particularly interesting was the discovery that the lift industry is in fact a very small world: after only a short while the names of experts like Fruin, Strakosch, Barney, Bukowski, Siikonen, Averill and the late Guylène Proulx, become familiar. It was a pleasant surprise to find out how much enthusiasm people working in the fire safety engineering branch share about common topics like high-rise evacuation and lifts. On numerous occasions my sparring partners and myself found ourselves forgetting the time and having to break off the discussion, and none of my many queries by phone or via the mail remained unanswered. Personally I can fully understand why so many people love this subject, as I have become one of them.

Many people have provided valuable and much-appreciated assistance during this thesis project. Jochem Wit, my thesis project supervisor at Deerns, is a leading expert in the lift industry himself and introduced me to this small, unique niche in the building industry. Jaap Wijnia is a fire safety engineer at Peutz and my other supervisor from the field: he provided valuable information and advice regarding the numerous aspects of fire safety and could offer useful feedback on many occasions. In extension, all members of my thesis project committee were a source of valuable criticism, often showing much more interest and patience than strictly required during this long project. The employees of both Peutz and Deerns also showed great interest for the subject: I am extremely grateful for all the help they gave me while also having to do their own jobs.

The TU Delft University of Technology has been an incredible source of support during all the years that I have spent there. People like Addy Schwartz, Theo Horstmeijer and Piet Jonkheer have made it possible for me to complete this education despite my physical limitations and will never realise how much I owe them.

Finally I would like to thank my friends, my family and in particular my mother for their patience and their help. So many people here have helped to solve the practical, day-to-day problems that it would be impossible to name them all, and they did it with a smile. Thank you.
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INTRODUCTION

Everywhere in the world, buildings are growing in height. Arguably the greatest challenge while designing ever-taller buildings, is the aspect of vertical transportation. Travelling times for building occupants need to be acceptable while maintaining the economic feasibility of the building by preserving as much valuable floor space as possible. These interests clash with one other, essential requirement: the safety of the building, and in particular the ability to evacuate the building occupants safely and within an acceptable time frame. The precarious balance between economic feasibility and fire safety has been a topic of discussion for a long time.

The conventional and well-known “In case of fire, use the stairs!”--rule becomes increasingly difficult to remain a realistic solution as a building’s height increases: a human’s physical capabilities are limited, even without taking into account any added limitations due to age or physical disabilities. This results in the logical choice to either limit the height of a building to fit required evacuation times or adopt tools to assist humans in the process of emergency egress. The fact that lifts aren't widely accepted as means of emergency egress but buildings continue to grow in size, shows however that this choice isn't as clear-cut as it seems.

The first papers suggesting lifts as a means of evacuation were published in the seventies. Since the attacks in 2001 on the World Trade Centre in New York, the discussion about integrating lifts into the evacuation process has gained momentum. Buildings in the Netherlands haven’t exceeded 190 meters yet: therefore this concept hasn’t been a topic of national discussion until recently. Official Dutch legislation only applies to buildings below 70 meters: for any building exceeding this height, Dutch law literally states that “solutions must be given that are at least as sufficient in comparison to buildings subject to the current legislation.” The absence of a more specific explanation as to what “sufficient” is, has caused an increasing amount of parties from the building industry to voice their concerns about the need for new legislation. A number of initiatives are in progress to offer guidelines that can serve as a base for future legislation in this respect.

In this thesis the possibilities, opportunities and risks surrounding the use of lifts during the evacuation process will be explored. The combination of lifts and emergency stairways as an integrated system will receive particular attention. The compiled list of conditions for a safe evacuation process is one of the main focal points of this research. The second focal point is the ideal procedure to evacuate people out of a building, given a certain building height, type and given a certain emergency situation. The goal of this thesis is to provide a guideline for the ideal evacuation strategy of high-rise buildings.

In order to provide such a tool, it must be based on a large archive containing the numerous possibilities, threats and strategies available. It is not possible to list all solutions for every possible threat however, and choices must be made between conflicting suggestions offered by the numerous sources available. Equally important is the conduction of a number of sensitivity analyses to uncover the influence of each factor in respect to the entire equation.

Note that this thesis covers a large area and is therefore quite general in nature. The goal of this thesis is to provide an overview of the developments regarding this subject and to serve as a springboard for more detailed research. The abovementioned tool will therefore be general in nature as well: the models themselves however have been designed with the ability to factor in more factors than traditional models (examples are the influences of fatigue and increased risk of blockages in stairwells over time due to accidents), making it possible to change and/or update the chosen parameters to fit the requirements and demographics belonging to the region or country in question. This leaves room for a critical review of the used parameters in future studies.
This thesis paper can be divided in roughly three parts:
- Part I provides general information from the relevant fields of expertise that surround the topic “evacuation using lifts”.
- From this context, Part II focuses specifically on the topic itself and describes the in-depth research done to answer the main questions posed in this thesis: is it viable to use lifts for evacuation in the Netherlands? What is needed to make evacuation via lifts safe? What is the best evacuation strategy? How much time will it take?
- Part III evaluates the proposed models, attempts to verify these models using two test cases and describes the conclusions and recommendations found regarding the use of lifts for emergency egress in the Netherlands.

Chapter 2 is still part of the introduction to this thesis. Besides defining the topic of this thesis, the goals and restraints, chapter 2 also provides an overview of the research process and the literature that is available on this subject.

Part I – General research
Background information is provided for three relevant fields of expertise: vertical transportation and lifts (chapter 3), legislation and standards (chapter 4) and building safety engineering (chapter 5).

Part II – In-depth research
Chapter 6 is basically a SWOT-analysis of lifts, describing the (S)trengths, (W)eaknesses, (O)pportunities and (T)hreats when using lifts in emergency situations. Chapter 7 addresses the weaknesses and threats to the lift system and offers solutions to protect the lift system and enable a safe, efficient evacuation process.

Now the focus shifts towards modelling the information into a number of evacuation scenarios (chapter 8). Chapter 9 describes the research done to determine a (modified) model for evacuation using stairways, introducing factors that the traditional models do not incorporate. Chapter 10 then combines the stairway model with a lift evacuation model, resulting in an integrated model through which the egress times of the different scenarios can be calculated.

Part III – Evaluation, verification and conclusions
Chapter 11 lists the calculation results of the developed models, using a large number of fictional building designs. These results are put to the test by two test cases, where the calculated results are compared to real-life evacuation data (chapter 12). Chapter 13 provides a final conclusion regarding all the results of this thesis and offers a number of recommendations regarding the use of lifts for evacuation in the Netherlands and options for additional research.
2 PROBLEM DEFINITION, APPROACH, CONSTRAINTS

The concept of evacuation using elevators has been discussed by the international community for over thirty years. High-rise buildings in the Netherlands however have only recently reached heights at which the interested parties have started a serious debate about the possible need to review the traditional rule of using stairs as the only means for emergency egress. The Belle van Zuilen (a project that has been cancelled in January 2010 due to the economic crisis) would have been 269 meters high, originally planned be built in 2014 in the city of Utrecht. It would have been a huge jump up from the current highest building, the Euromast (185m), which has more resemblance with a large radio tower than a commercial (office) building. The current holder of the second place is the Maastoren (165 m), completed in December 2009, followed by the Delftse Poort (151m), built in Rotterdam in 1991.

The abovementioned Belle van Zuilen would have been the first building in the Netherlands to incorporate “normal” lifts into the evacuation procedure. The necessary knowledge to make a proper design that is guaranteed to be functional and realistic, was not available however. Burgfonds, the real estate developer responsible for the design and building of this project, had to import the knowledge concerning techniques, requirements, procedures and human behaviour from other countries with more experience on this subject.

A number of foreign countries have much more experience with high-rise building projects, and have been working with the concept of using lifts as a means of evacuation. The 2001 WTC attacks have caused the discussions about this topic to intensify; the U.S. National Institute of Standards and Technology (NIST) has published the results of extensive research in 2009. In Kuala Lumpur, the 2001 tragedy has been cause for extending the use of shuttle lifts to both towers in their evacuation protocols (Ariff, 2003). The Burj Dubai has also incorporated an evacuation protocol using lifts, designed in cooperation with Otis. There are however much more high-rise buildings with their own solutions concerning (fire) safety and evacuation.

An extensive literature study can compile a list with solutions, suggestions and criticism and serve as a database from which suggested strategies can be compared. This will answer many questions and can prevent any “reinventing the wheel”, so to speak. Besides showing what knowledge is already available on the subject, a literature study can also point out the areas where more research is necessary. During and after collecting this information, it will need to be processed. Comparisons will need to be made between the different legislations, protocols, opinions and calculation parameters. From the mounds of data available, a comprehensive overview will have to be compiled and a balance needs to be found between a general overview of the entire subject that barely scratches the surface and a research project that focuses in depth on one detail, but offering no general insight about the subject.

An important prerequisite is that the results of this research project can be applied in the Netherlands. Keeping in mind that much of the existing literature has been written from the perspective of the building industry in the U.S. or Asia, cultural and legislative
differences cannot be ignored. It could prove quite difficult to adopt the strategy used in one country and observe the alterations necessary to use it in another.

2.2 Problem definition

The current amount of knowledge and experience in the Netherlands regarding evacuation methods using lifts is insufficient. Other countries have more knowledge and experience on this subject, but official legislation specifically covering the requirements demanded of evacuation lifts is still non-existent (save a few exceptions). In general, the information provided by the various international experts is spread out over a large number of separate publications.

The following summary can be made of paragraph 2.1:
- Information is needed concerning the relevant topics. This includes information about vertical transportation in general, current safety measures in regard to emergency egress and developments in this respect.
- It is necessary to take into account any differences in regards to legislation and building culture of different countries.
- The information needs to be compiled and structured in a user-friendly way.
- The information and possible tools need to be applicable for the Netherlands.

2.3 Thesis Goals

This thesis project strives to compile all the publications available into a list of conditions for a safe evacuation process (both physical and organisational). The second focal point is the ideal procedure to evacuate people out of a building, given a certain building height, type and given a certain emergency situation. The acquired information should result in a set of models that can calculate evacuation times when using different procedures. The fastest procedure can be found by comparing evacuation times.

The overall goals of this thesis are:
- To determine what the necessary prerequisites are to ensure safe usage of lifts for emergency egress.
- To gather the knowledge required to decide if/when lifts are beneficial in the evacuation process and how lifts can be integrated into this process.
- To design a tool and/or guideline that can aid a designer in the decision how to evacuate a certain building, given a certain emergency situation. The emphasis of this tool will be the integration of lifts into the evacuation process.

Note the possibility that evacuation via lifts may be inadvisable, at least in some situations. In any case, the recommendations given in this thesis paper must be based on unbiased research, where viability of lift evacuation has not been (pre-) determined.

2.4 Approach

2.4.1 Defining the scope of the thesis

The first task was to gather the information necessary to understand what the problem was, and then how to solve it. This sounds obvious, but lift technology is an area of expertise belonging to mechanical engineers, and even then the world of vertical transportation and lifts belong to a select group of specialists. Vertical transportation and building safety in a more general sense is the domain of architects. A civil engineer or, more specific, a building engineer has more specific knowledge about topics like structural integrity, transportation capacity calculations in general, the construction process and building physics. A topic like the possibilities of using lifts in an evacuation
process therefore demands a multidisciplinary approach with input from many different sources.

It becomes clear that, in order to keep the task manageable, boundaries will have to be set to limit the scope of this project. A basic level of knowledge and understanding of lifts is necessary, but this thesis paper will limit itself to the relevant information about lift design, lift grouping, zoning and the design capacity of lifts in a building. Furthermore, the focus will be on the structural, physical and logistical requirements in respect to the environment of the lifts: the design of the lifts themselves is best left in the hands of the lift manufacturing companies.

This limits the number of relevant topics that need to be researched. They can roughly be grouped as such:
- Basic lift design.
- Vertical transportation: lift capacity design, lift grouping, zoning etcetera.
- Pedestrian egress models: handling capacities of corridors, portals and stairwells.
- General safety design in buildings; safety design in respect to lifts.
- Human behaviour in emergency situations; communication and organisation.
- Current legislation and standards. Differences between countries, keeping in mind that, in the end, the final product should be applicable in the Netherlands.
- Current debate regarding the usage of lifts as means of evacuation. Ideas, suggestions, criticism.

2.4.2 Thesis research locations

In addition to the literature research, two engineering & consultancy firms have been approached with the request for an internship. The experience and expertise of these companies are an excellent addition to the theoretical information found in books and other publications, ensuring that the final product is practical application that can be used in the "real world". They can provide valuable information, advice and even contacts with other firms or specialists where necessary. Both firms are also participants of the Convenant Hoogbouw, an initiative of the Dutch institution for norms and regulations or NEN, to create a new set of guidelines for buildings higher than 70m in the Netherlands.

Deerns is a firm that, among others, is highly specialized in transportation and logistics in buildings. Peutz has specialized itself more in the area of building physics, among which the behaviour of fires, airflow and ventilation. Both firms have provided valuable information and advice concerning these two aspects of the thesis project.

2.4.3 Creating a guideline

Based on all this research it should be possible to create a guideline with the optimal evacuation procedure designs. An office building has different characteristics compared to a residential building, and a trash can fire requires a different procedure than that of a bomb threat. Like in the research stage, constraints are necessary to keep the product manageable. A number of emergency situations will be considered, and a number of possible evacuation procedures will be described. The goal is to find the optimal procedure, given a certain building type and a certain emergency.

How will this optimal procedure be determined? A group of equations will be chosen to define pedestrian evacuation by stairs, by elevators and by a combination of the two. The basic theory behind these calculations is that the physical ability of pedestrians to travel via emergency stairways decreases over time and with larger building populations. This means that at a certain building height, the method of evacuation shifts in favour of using lifts. By determining the height above which lifts are the preferred method of travel, the optimal evacuation procedure becomes much clearer. One of the main goals is thus to create a tool which can calculate the optimal solution for the evacuation procedure.
2.4.4 Checking the results and determining reliability

Once a first draft has been created of this guideline and calculation tool, it is important to check its accuracy and reliability, for as far as that is possible. A few existing buildings with well-documented data regarding evacuation are ideal test cases to check the calculation models. In addition a number of safety analyses can be conducted to determine whether certain factors are improperly balanced, causing their influence to be uncharacteristically large or, on the contrary, exceptionally small.

Because the parameters used for factors like the average pedestrian speed are very important for the final results, the calculation tool should offer the possibility to alter these factors. The values chosen in this thesis can then be changed or updated if necessary.

2.5 Constraints

As stated in previous paragraphs, constraints are necessary to keep the project manageable. There are only so many building types one can take into account, and building cultures can vary greatly between countries. The constraints also provide a way to emphasize the priorities of the thesis project.

2.5.1 Boundary Conditions

This thesis project has been subjected to the following boundary conditions (Dutch: randvoorwaarden):
- For legislation purposes, Dutch law is the determining condition, followed by European and international law.
- Confidentiality protocols of firms in general can limit the amount of available information, due to competition in, for instance, the lift industry.
- The publication of this thesis project may be delayed for a maximum of 6 months due to confidentiality agreements with companies involved with this thesis and its contents.
- This research has been conducted on a low budget. One of the causes is that this thesis paper is meant to be a free, open source document.
- The maximum time frame for this thesis project is 18 months. The expected time frame is 12 months (September 2008 – August 2009).

2.5.2 Starting points

The following starting points (Dutch: uitgangspunten) have been assumed:
- Dutch building legislations, procedures and methods will be used when determining the best protocols, demographic data etcetera.
- This project will focus on the general characteristics and practical use of lifts rather than going into technical details and innovations in the lift industry.
- Lift manufacturers are able to define and quantify the requirements demanded of the environment of the lift installations (shaft, lobby and machine room) in order to guarantee that the lift remains in working order.
- Although the economic feasibility of the safety measures will be taken into account, this thesis will not focus on the economic feasibility of (high-rise) buildings in general.
- This thesis project will focus mainly on buildings with a height between 70-250 meters. Higher buildings in the Netherlands are considered to be unique projects needing special (additional) attention. Many buildings below 70 meters may prove to be ideal for evacuation via lifts, but these possibilities will need to be explored in additional research projects.
- The impact of suggested safety measures on the construction and/or layout of a building will be taken into consideration. However: the possible challenges when retrofitting existing buildings is a subject for additional studies.
2.6 The research process

This paragraph has been added to give some insight about the way that the information for this thesis has been collected. Like a design process in general, the literature study has proven to be a cyclic process: the important names and general regulations are found soon enough, but along the way one discovers that some data isn’t as reliable as it was portrayed to be, and that different countries turn out to have fundamentally different approaches towards safety design, which means that the opinions of some leading authorities of one country may not be applicable for a different country.

2.6.1 Initial contacts

The first step towards finding relevant information was to search the internet for potential contacts who were relatively close by and possessed the know-how to direct the author towards relevant documents within a short time frame. This resulted in several meetings with Dutch professionals who had more inside knowledge about the lift industry and fire safety design. One example of these new contacts is Koos van Lindenbergh of the Dutch Liftinstituut, the leading Dutch institution concerning lift safety inspection and certification. Another new contact is Klaas de Winkel, of the Nederlands Normalisatie Instituut (NEN): the NEN is the official Dutch institution for standardisation and legislation, as explained in paragraph 2.4.2. Other contacts include representatives of the fire departments of Amsterdam and Rotterdam and Peutz and Deerns, the aforementioned engineering and consultancy companies who each provided a four-month internship. All these contacts provided documentation they deemed relevant, resulting in a lot of useful information within a short period.

2.6.2 Sorting out the available literature and writing the thesis

The number of documents available on this subject was astounding. In the reference lists of the various articles, some names kept returning however, like Fruin, Strakosch, Barney, Siikonen and Bukowski. It soon became clear how small and highly specialised this niche is inside the building industry.

Internet and library research could become more focussed now, and the important references to other books and articles could be gathered, if available in the library or accessible via the internet for a reasonable price. After deciding upon a framework for the desired information a table of contents could be set up, illustrating this framework and the necessary steps to reach the desired result.

The actual writing process for this thesis started by compiling the basic information necessary from the different fields of expertise. Many ideas came to mind while studying the literature and writing the first chapters: in order to remember these epiphanies, the latter chapters started out as bundles of “napkin comments”. It didn’t take long however to understand that the thought of being able to bring genuinely original, new ideas to the drawing table was a naive one. Every devised idea or strategy could be found in articles as the months passed by and the research deepened. This shouldn’t be regarded as a negative conclusion though: it was simply an affirmation of the importance of certain aspects of the strategies needed to make it possible to integrate lifts into the evacuation process.

2.6.3 Important literature

During this thesis project, a number of documents have proven to be key anchors. During the initial stage, the booklet published by Otis B.V. in 1992 and the CIBSE Guide D (2000) were excellent introductions to the basic technical data about lift components and systems. The books written by George Strakosch (1998) and Gina Barney (2003) were an excellent introduction to lift design and illustrated the basic principles upon which the desired lift capacity is determined.
In her book (2002), Barney also pays a lot of attention to pedestrian traffic behaviour, based for a large part on John Fruin’s work (1987). Based on the fact that just about every paper about pedestrian traffic design refers to this work, Fruin can be considered the pioneer of this area of expertise. Where Fruin uses parameters based on human characteristics of the 1970’s however, current demographic developments like population ageing and rising obesity rates need to be taken into account. Fahy and Proulx (2002) have written a paper with data concerning lower movement speeds of people with disabilities, based on tests in Northern Ireland. Many other papers refer to this work, which also touches the subject of group behaviour. Additionally, Fruin’s macroscopic approach regarding pedestrian traffic may have become outdated as computer simulation tools have evolved. Experts like MacLennan et. al (2008) are increasingly favouring a microscopic, risk based simulation tool.

In regard to computer modelling, one of the benchmark documents describing the first computer models was ELVAC, written by John Klote and Daniel Alvord (1992). This program is limited to evacuation by lifts only. In turn, this model was based on earlier models by Strakosch (1983), Bazjanac (1977) and Pauls (1977). Since then there has been a huge development regarding computer models, or computer simulation programs, to be more precise. These simulation programs allow for the shift from a macroscopic to a microscopic approach. This is especially useful when integrating stairs and lifts into a single model, and when taking individual human behaviour into account.

There are a number of important events that shaped the discussion about using lifts for emergency egress. Bazjanac proposed using lifts in this role in 1974, then presented calculations in 1977. Although a select number of specialists kept debating the subject through the years, it was the Americans with Disabilities Act of 1990 that triggered a newfound interest for this subject. The National Fire Protection Association, the American Society of Mechanical Engineers (ASME) and the Council of American Building Officials (CABO) sponsored a symposium in 1991 (Klote et al. 1993). The National Institute of Standards and Technology (NIST) held a workshop in 1992 (Klote et al. 1993 (2)), with a follow-up workshop in 1995 hosted by ASME. The WTC terrorist attack in 2001 was another major event that fuelled the debate about the usage of lifts for emergency egress purposes. A host of authors presented arguments for and against the concept in professional journals like Elevator World. Several organisations like the Council on Tall Buildings and Urban Habitat (CTBUH), SFPE, NIST and ASME hosted conferences and workshops where this topic was the centre of attention. The attention surrounding this topic had now become so large that government organisations around the globe started considering lifts as a viable tool for, at least, the fire department.

2.6.4 Legislation and standardisation

The Dutch Building Codes (Bouwbesluit) were essential during the research. The Dutch Institute for Standardization and Normalisation (NEN) creates the official norms upon which Dutch building legislation is based. The SBR guidelines were also key documents in order to synchronise the recommendations with the Dutch building environment. In a slightly larger context, the European norms (EN) are equally important and usually coincide with the Dutch norms.

The two key foreign institutes concerning legislation and standardisation were the U.S. National Institute of Standards and Technology (NIST) and the British Standards Institution (BSI). Comparing the different approaches of these building legislations proved to be very insightful. For a global perspective the International Organization for Standardization (ISO) has been an important reference.

The CTBUH (Council on Tall Buildings and Urban Habitat) has published a relatively simple, comprehensive document called “Emergency evacuation Elevator Systems Guideline” (2004). This guideline covers the basic principles of evacuation by lifts and has proven to be an anchor point for this document.
Part I

General research
Vertical transportation is a crucial subject when designing high-rise buildings: in fact, the very definition of a high-rise building is based on the applied means of vertical transportation. Merriam Webster’s Dictionary defines a high-rise building as: “being multi-storey and equipped with elevators.” The Dictionary of Real Estate Terms provides a slightly more detailed description: “generally a building that exceeds 6 stories in height and is equipped with elevators.” (Barney 2003). The UK building code has typically defined a building as a high-rise, requiring special safety features to be installed, if it has occupied floor levels located above 30m in respect to ground level (HMSO 2002); the building code of the United States of America has typically defined this height at occupied floor levels located above 23m (75 ft) in respect to ground level (NFPA 2006).

In general, people associate high-rise buildings with the skyscrapers that define the skylines of major cities all over the world. A building of “only” 15 stories high already provides significant challenges however.

This chapter describes basic aspects of vertical transportation within buildings. Stairs, escalators and lifts each have advantages and drawbacks, which determine what the best choice is when designing a system for vertical transportation.

### 3.1 Stairs versus lifts

There are several means available for vertical transport in buildings. Most common are stairs, escalators and lifts. In order to reach his destination inside or outside the building, a building occupant will select the route he prefers, possibly using a combination of these means to cross any vertical distances he encounters.

Lifts are used in almost all buildings of more than a few stories high. Whether a building occupant uses the stairs or a lift depends on his or her personal preferences. Stair usage depends on the number of floors which must be travelled and generally doesn’t exceed 6 floors (Barney 2003). This explains the definition mentioned at the beginning of this chapter.

<table>
<thead>
<tr>
<th>Floors travelled</th>
<th>Usage up</th>
<th>Usage down</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80%</td>
<td>90%</td>
</tr>
<tr>
<td>2</td>
<td>50%</td>
<td>80%</td>
</tr>
<tr>
<td>3</td>
<td>20%</td>
<td>50%</td>
</tr>
<tr>
<td>4</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>5</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>6</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

*Table 3.1: Stair usage, compared to lift or escalator use (Barney 2003)*

Table 3.1 shows the average person doesn’t bother to traverse more than six floors by stairs, under normal conditions. This means that vertical transportation in tall buildings is heavily dependant on its lift system.

### 3.2 The anatomy of a lift

There are many different types of lifts available: one of the main ways to define them is to differentiate the different lift drives. Examples are hydraulic lifts, scissor lifts, platform hoists and rack and pinion lifts. The lift drive most commonly known and used in (high-rise) buildings are traction lifts: therefore only traction lifts will be described for the remainder of this section. The aim is to provide basic information about a lift’s components, while keeping this information limited to what is relevant within the scope of this thesis.
The main components of the lift are its prime mover (an electric motor), the lift car, counterweight, guide rails, entrances, safety gear and governor, buffers, ropes and fixtures (i.e. buttons, indicators and switches) (CIBSE 2000).

3.2.1 The prime mover

Traction lift machine assemblies can generally divided into gearless and geared machines. The assembly typically comprises a drive motor, drive sheave, bedplate, brake, direct current armature, support bearings and, possibly, a deflector or double wrap sheave.

Gearless machines have generally been used for high-speed lifts, i.e. speeds from 2,5 m/s to 10 m/s (CIBSE 2000). They are, however, now used for all speeds, including low speeds. Size, shape and weight may vary considerably between manufacturers but the basic principles and components will be the same. The power developed is transmitted directly to the driving sheave.

In case of geared machines, the motor transmits its power to the traction sheave or drum via reduction gear, creating a reduction in speed and a higher weight capacity. Geared machines are generally used for speeds between 0,1 m/s and 2,5 m/s and are suitable for loads from 5 kg up to 50.000 kg or more (CIBSE 2000).

The brake drum is usually formed as an integral part of the driving sheave and this may be one of several types, each one having its advantages and disadvantages. The brake is used only during emergency stopping and when at rest to hold the lift car during loading. Under normal operating conditions, speed controls are employed to bring the car to rest without the use of the brake.

The primary function of a drive sheave is to provide guidance and (additional) traction for the lift ropes. Deflector sheaves facilitate the required spacing between lift car and counterweight: this ensures a proper vertical alignment of the lift cables.

3.2.2 Machine positions

The preferred position of a machine room is the top drive arrangement, i.e. where the lift machinery is positioned directly above the lift shaft, see figure 3.1. Other machine positions can be utilised to minimize headroom requirements. However, each of the alternative options may have implications in terms of additional costs, increased running noise etcetera. Locating the machine at the bottom of the lift shaft for instance usually results in an upward pull, which can drastically reduce the sheave shaft load capability. Besides positioning the machine room under the shaft instead of on top, it is also possible to place the machine room adjacent to the shaft.

So-called “Machine room-less” have appeared on the market in recent years (CIBSE 2000). In these special lifts, the machine and other equipment that was traditionally located in the machine room are located in the lift shaft or landing areas.
3.2.3 Safety features

Lift systems are designed according to the “fail-to-safe” principle: this means that the system will automatically revert to a safe state if a failure occurs (Harms-Ringdahl 2001). This makes lifts one of the safest methods of transportation today. Lifts have a large number of components to ensure maximum safety. The Dutch/European safety norm NEN EN 81-1 describes the necessary safety measures for traction lifts.

Guide rails ensure a smooth and safe ride for both the lift car and the counterweight, keeping them in place and preventing dangerous horizontal deflections. A proper positioning and alignment of these guides is therefore extremely important.

The most common method to open and close lift doors is an electric door opener mounted on top of the car (CIBSE 2000). When the lift arrives at a floor, a mechanical device couples the car doors to the landing doors. As the car doors open, they also pull open the landing doors. This method prevents the landing doors from being opened if the car is not at a floor. In addition, the closing speed of lift doors is limited to reduce the risk of injury. For the same reason, lift doors are required to be equipped with passenger detection devices, see figure 3.3.

An example of a typical door safety device is a mechanical safety edge. Any deflections of this edge caused by striking an object, will cause the doors to reopen. More common than this simple, low-tech method are electronic detection devices like photocell detectors (in combination with reflectors) or an electronic detection field, as illustrated in figure 3.3. This allows for detection of obstructions without the need of physical contact, which makes the doors less susceptible to damage. In addition, electronic detection
devices can be used as a “door open” (dwell time) monitor (CIBSE 2000). By modifying the dwell time in response to obstructions, unnecessary reopening can be avoided.

Overspeed governors have been used on lifts almost since the first lifts were installed (CIBSE 2000). The purpose of the overspeed governor is to stop and hold the governor rope with a predetermined force in the event of the descending car or counterweight exceeding a specific speed.

A typical centrifugal governor works as followed: as the sheave rotates, the flyweights move outward due to centrifugal force. At a predetermined speed, the weights strike a release mechanism that causes the rope-clamping device to grip the governor rope.

The rope-clamping device is designed to allow the rope to slip through its jaws if the load on the rope is too great. This ensures that the safety gear (the mechanical clamping devices fixed onto the car frame) stops and holds the car rather than the governor. The prime function of these clamps is to grip the guide rails and thus prevent the uncontrolled descent of the car, in case of failure of the ropes. For speeds up to 1 m/s instantaneous safety gear can be used (CIBSE 2000). It is almost instantaneous in operation: the small stopping distance results in a high strain on both the equipment and the passengers. Therefore progressive safety gear is used for higher speeds: here the clamps apply a limited pressure on the guide rails, causing the lift car to slow down more gradually before reaching a full stop, see figure 3.5.

Besides triggering the rope clamping device and the safety gear, overspeed governors are also provided with an electrical switch that removes power from the lift motor. If the governor has been activated, it will need to be reset, either by raising the car or manually. This needs to be done by a qualified person, who can determine the cause of activation and who can inspect the lift equipment before allowing it to be used again.

**Figure 3.4: Detail of an overspeed governor (left); lift car frame, with safety gear and connection to the governor rope (right) (CIBSE 2000)**

**Figure 3.5: Progressive safety gear (CIBSE 2000)**
At the top and the bottom of the lift shaft, additional safety measures are placed. In the lift pit, the most obvious ones are the buffers. The buffers are placed below the lift car and the counterweight: in case either one of these overtravels into the lift pit, these buffers slow them to a halt by absorbing the kinetic energy. This basically can be done in two ways: energy accumulation (springs, rubber) and energy dissipation (hydraulic buffers, CIBSE 2000).

Although the buffers are designed to bring a moving lift car (at 115% of rated speed) to a stop while subjecting the passengers of the car to a maximum retardation of 1-2.5 GN (CIBSE 2000), this safety measure is not meant to absorb a ‘falling’ lift car, but rather as a backup if a descending car ‘misses’ its bottom stop.

A number of consecutive kill switches are situated against the wall at the top of the lift pit: if the lift descends any deeper than it should at bottom level, these switches should activate the mechanical clamps on the lift car if they hadn’t already been activated by the overspeed governor. In addition, all electrical power to the lift is cut and the system remains locked until a trained professional restores the lift to working order. Similar safety features can be found at the top of the lift shaft.

3.3 Lift traffic: basic definitions

The vertical transportation business is a specialisation that uses a number of specific terms to define traffic flows inside buildings. Traffic flows have different values, depending on the building’s function (office, residential etc.). This paragraph will explain a few of these terms that are relevant within the scope of this thesis.
3.3.1 **Uppeak, Down peak, Lunch peak**
The intensity of traffic flows in a building varies greatly. In an office building for instance, the traffic pattern is “subject to a strict regime of fixed starting, break and leaving times” (Barney 2003). Figure 3.7 shows the typical traffic flow in an office building.

![Figure 3.7: Typical traffic flow for an office building via lifts, observed from the main lobby (Strakosch 1998)](image)

When the day starts and the building’s occupants arrive to work, there is a relatively large amount of people wanting to go to their office, resulting in a peak of up-hall calls for the lift system to service. This so-called “Uppeak” (Barney 2003) depends on the times that the businesses housed in the building start. At the end of the working day (usually after 17.00 hours), the building’s population leaves the building to go home, resulting in a large number of down-hall calls. This is called the evening down peak (Barney 2003). In the middle of the day the lift system will likely register one or more sets of uppeaks and down peaks, depending on the lunch periods of the building occupants, and will service the ‘normal’ calls, otherwise known as interfloor or two-way traffic (Strakosch 1998, Barney 2003).

Traffic flows have different values, depending on the building’s function: the traffic flows in a residential building for instance follow less rigid schedules than those of an office building. Uppeaks and down peaks in a hotel are likely to follow checkout times, breakfast/lunch/dinner times, etcetera. For this reason the required amount of lifts vary for different building types.

**5-minute peak value**
The arrival rate pattern for the morning uppeak has been illustrated in figure 3.8. It describes the arrival rate of building occupants in respect to the required starting time at work. Note that the arrival rate has been described in terms of passenger calls per hour, for a period of one hour (Barney 2003).

![Figure 3.8: Detail of uppeak traffic profile (Barney 2003)](image)
The profile of this curve is often idealised in terms of a 5-minute peak value, taken as a percentage of the total building population (the wide hatched area of figure 3.8, Barney 2003). In practice, the lift industry designs a lift installation to handle the number of passengers requesting service during the heaviest five minutes of the uppeak condition (Barney, 2003). A system designed with the capacity to handle the entire peak would become too large and thus too expensive.

Figure 3.7 shows that the down peak is usually more intense than the morning uppeak, with higher demands and a longer duration. It can be argued that arrival times may differ more in the morning (commuters reserve more time to take heavy traffic into account, for instance), and that the departure time for the building’s occupants is more accurate (for example 17.00 hours, whether you are a commuter or you live one block away).

Fortunately a lift system can be shown to possess 50% more handling capacity during down peak than during uppeak (Barney 2003). This is because during down peak a lift car fills at 3-5 floors and then makes an express run to the main terminal. This reduction in the number of stops results in a shorter round trip time and hence a greater handling capacity during down peak (Barney 2003).

3.3.3 Up Peak Handling Capacity (UPPHC) and Round Trip Time (RTT)

“The handling capacity of a system (UPPHC) is the total number of passengers that it can transport in a period of 5 minutes during the uppeak traffic condition with a specified average car loading” (Barney 2003).

The lift industry defines the five-minute peak value as illustrated in figure 3.8 to be the value upon which to base the needed (total) lift capacity of a building. This value has been generally accepted to represent a reasonable waiting time.

In order to calculate the capacity of a building’s lift system, it is necessary to define the time that a (single) lift car takes to make a trip up and down the building: “The round trip time (RTT) is the time in seconds for a single car trip around a building from the time the car doors open at the main terminal, until the doors reopen, when the car has returned to the main terminal floor, after its trip around the building” (Barney 2003).

With the RTT you can define the 5-minute handling capacity (UPPHC) of a single car as:

\[
\text{UPPHC} = \frac{300 \times \text{average number of passengers per trip}}{\text{RTT}} \quad (\text{Barney 2003})
\]

where the 5 minutes have been shown as 300 seconds.

Equation (3.1) is one of the most important equations used in lift design (Barney 2003).

3.3.4 Calculating the UPPHC of a building

In order to calculate the 5-minute handling capacity (UPPHC) of a lift system, additional definitions are needed. The first value is the number of passengers carried, which can be defined as \( P \). Note that \( P \) hardly ever equals the defined rated car capacity (CC), i.e. the maximum amount of people allowed inside the lift car. Barney (2003) assumes a
traditional passenger filling to be 80% of the car capacity. With this in mind the UPPHC can be rewritten as:

\[
UPPHC = \frac{300}{RTT} \times P = \frac{300}{RTT} \times \frac{80}{100} \times CC
\]

(Barney 2003)

In a lift system with an L number of cars, equation (3.2) becomes:

\[
UPPHC = \frac{300}{RTT} \times P \times L
\]

(Barney 2003)

Note that in a lift system the "interval" between successive lift car arrivals isn’t the same as the round trip time of a single lift car: figure 3.10 shows how a lift system is more efficient than a single lift:

The uppeak interval \(UPPINT\) can therefore be derived as "the average time between successive lift car arrivals at the main terminal floor with cars loaded to 80% of rated car capacity during uppeak traffic conditions." Therefore one could describe the UPPHC as:

\[
UPPHC = \frac{300}{UPPINT} \times P \quad \text{[persons/ 5 minutes]} \quad \text{(Barney 2003)}
\]

with \(UPPINT = \frac{RTT}{L}\) [s]

The information above is enough for a designer to calculate what percentage of the entire building population can be served in 5 minutes. "The population served in the uppeak 5-minutes is defined as the ratio of the UPPHC and the building population given as a percentage" (Barney 2003):

\[
\%POP = \frac{UPPHC}{\text{building population}} \times 100 \quad \% \quad \text{(Barney 2003)}
\]

The following example can provide more clarification: A building is served by 3 lifts with each an RTT = 150 s and a rated car capacity of 10 passengers. The building population is 400 persons. This makes the uppeak interval: \(UPPINT = 150/3 = 50s\).

\[
\Rightarrow UPPHC = \frac{300 \times 80}{50} \times 10 = 48 \text{ persons/ 5 minutes.} \Rightarrow \%POP = \frac{48}{400} \times 100 = 12\%.
\]

In other words: this building’s lift system can handle 48 persons or 12% of the building population in 5 minutes.

A good indication of generally utilised UPPHC values are: 11-14% for offices, 5-6% for residential buildings and 14 -18% for hotels. Residential buildings are less densely
populated than office buildings, and the lift traffic is spread out much more over the day. In hotels, people tend to require more personal space than in office buildings, resulting in less occupants per lift car. At home occupants are less in a hurry, hotels place more value on customer satisfaction. This roughly explains the differences between the required lift handling capacities of different building types.

### 3.4 Building zones and lift groups

When a building’s height (and thus the number of floors) increases, the journey time for passengers using lifts increases as well. The higher number of stops increases both the passenger waiting time and the passenger journey time. Attempting to counteract this deterioration in performance simply by increasing the number of lift shafts in order to maintain an acceptable handling capacity isn’t the best approach: the solution is to limit the number of floors served by the lifts. A rule of thumb is to serve a maximum of 15-16 floors with a lift, or group of lifts (Barney, 2003).

The concept of zoning comprises of dividing a building into zones of an x number of floors: a group of lifts is constrained to serve the floors of the zone it has been assigned to. There are two forms of zoning: stacked and interleaved (see figure 3.11).

A stacked zone building is where a tall building is divided into horizontal layers, in effect, stacking several buildings on top of each other (Barney, 2003). This form is a common and recommended practice for office and institutional buildings, and is often preferred over interleaved zoning.

#### 3.4.1 Transfer floors and sky lobbies

Most high-rise buildings provide some means to travel between (stacked) zones. This is sometimes achieved by overlapping zones (Petronas Towers), introducing extra stops (Sears Tower) or shuttle lifts (World Trade Center - NY). These transfer floors provide a valuable horizontal link between these zones. Note that without these transfer floors a person wishing to travel from, for instance, a floor in the high-rise zone to a floor in the mid-rise zone would be forced to first head back down to the main terminal floor, situated at ground level, in order to switch to the mid-rise lifts. Transfer floors give building occupants the option to switch between zones without too much added travel time.

A tall building can be divided into a number of zones, like for instance a low-rise, mid-rise and high-rise zone. If the service is directly between the aforementioned zones and the main terminal floor (situated at ground level or a sky lobby), that cluster of zones is called a “local” zone. In very tall buildings of 70 floors or higher, local zoning becomes impractical and shuttle lifts are employed to take passengers from the ground level main lobby to a “sky lobby” (Barney, 2003). Passengers disembark at the sky lobby and take the local lifts to their final destination, see figure 3.12.
The configurations illustrated in figure 3.12 are an indication: in reality each lift configuration varies as much as each different building. With all the different lift manufacturers, desired handling capacities and design philosophies, it is impossible to provide rigid guidelines about the number of floors that one zone encompasses. This notion may provide a challenge, especially if one would want to design a general (evacuation) guideline with recommendations based upon these zones.

As can be seen in figure 3.12, local zones between sky lobbies and the ground floor can be stacked, improving core efficiency and saving valuable floor space. This vastly increases the possible height of a building while keeping the passenger journey time reasonable. At for instance the Sears Tower in Chicago, the capacity of these shuttle lifts has been increased by using double deck elevator cars: note that, in this case, the sky lobbies need to be two stories high as well.

3.4.2 Safety design considerations

An important note is that the shaft of a lift appointed to one zone does not have any (normal) lift doors at other zones. In other words: you cannot use mid-rise lifts to service the low-rise floors, simply because there are no landing doors through which you can access these lifts.

In some buildings that don’t have separate fire-fighter’s lifts, a number of lifts servicing the high-rise zone are designated the dual function of fire-fighter’s lift. These lifts are required to have lift doors at all floors, including those of the low-rise and mid-rise sections. Note that these lifts need to be reserved for the fire department: this means that in general, a dual use as ‘normal’ evacuation lifts for the building’s population is not allowed (unless specific arrangements are made with the local fire department officials). In this case the lift capacity of the high-rise zone during an evacuation scenario is decreased in comparison to its ‘normal’ capacity.

Dutch regulations (NEN 81-1) require an access point into the lift shaft at least once every 11 meters (normally three floors) in case of emergencies. These access points are not suitable however for public use. Note that these access points are in fact ‘holes’ in the shaft structure: depending on their location and the fire resistance of the access doors, they are a possible liability in case of fire and/or an explosion. Normally the landing doors themselves are considered viable access points for maintenance or emergency rescue personnel. In mid-rise and high-rise sections however, maintenance doors need to be installed in the zones that don’t have ‘normal’ landing doors.

A last important observation regarding building zones is that the boundary between two zones is different when regarded from the perspective of building traffic flows or the perspective of fire safety engineering. Where transfer floors and sky lobbies provide a clear boundary between two zones, (horizontal) fire compartmentalisation is more complicated due to the extra space usually needed both above and at the bottom of the
shaft (machine room, shaft pit). This means that the actual space that needs to be
enclosed and protected is larger. Lift safety measures are described in more detail in
chapter 6.

3.5 Lift control systems

While it is useful to understand the physical components of a lift, understanding the way
in which they are controlled is essential when using them as a link in the building's
evacuation design. This paragraph describes the general methods to control lifts and lift
groups.

Single lifts and lift groups equipped with automated control systems are able to operate
at a very high efficiency; even before the era of the digital computer and when relays
were implemented, the developed ideas were ingenious (Barney 2003). Note that a “hall
call” is the term used for the summoning of a lift while waiting at a landing, and a “car
call” is the assignment that the passenger gives once inside the lift (usually by pressing
the button of the destination floor).

3.5.1 Single Call Automatic Control

Single Call Automatic Control, or automatic pushbutton (APB) control is the simplest
form of automatic lift control (Barney 2003). Once a passenger presses a button to
indicate his destination, the lift car moves directly to that floor, ignoring any hall calls
while en route. This essentially means that the lifts usually carry only a single
passenger, which results in a very low lift handling capacity.

3.5.2 Collective control

Collective control is the most common form of automatic lift control. In this case
registered hall calls follow the floor order rather than the order in which the pushbuttons
were pressed. A number of control types can be designated to the general term
“collective control”.

Non-directional collective control provides a single pushbutton at each landing (Barney
2003). A hall call is registered by the lift, regardless of the direction the person wishes to
travel to. This means that the lift doors will open for the waiting passenger: if the lift is
going up and the passenger wishes to travel down, that passenger will either need to
wait and push the pushbutton again, or step inside and travel along upwards before
going down. This illustrates the reduced efficiency of this method.

Full collective control or (directional collective control) provides each landing with an ‘up’
and a ‘down’ pushbutton. The lift stops to answer both car and hall calls in the lift
direction of travel, in floor sequence (Barney 2003). This control type is suitable to serve
a few floors with some interfloor traffic. This is a very common control system, with
which most people are familiar.

3.5.3 Destination control

With destination control or hall call allocation (Barney 2003), the conventional up/down
buttons at a landing are replaced with a panel. A passenger “dials” the destination floor,
using the panel: a screen informs that passenger which lift he needs to wait for (for
instance lift D), and once the lift arrives, it brings the passenger to his destination without
needing an additional car call.

This method requires an adjustment from the passengers, but most people nowadays
are familiar enough with keypads and similar technology to be able to learn the
procedure without too much effort.
The advantage of this method is that the group traffic controller knows the intended destination of passengers in advance, and can track every passenger from registration to destination. This information can be very useful for intelligent group traffic control systems, see paragraph 3.6.

One example of its use is the ability to group passengers heading to common destinations, which can significantly reduce round trip times during the morning uppeak. Another example is the possibility to add a button for people with disabilities (see figure 3.13), allowing the system to hold the lift doors open for a longer period of time, or activate spoken directions for example.

### 3.6 Group traffic control systems

Interconnecting the lift systems can greatly enhance efficiency in buildings with multiple lifts are installed. A group of lifts can be defined as “a number of lifts placed physically together, using a common signalling system and under the command of a group traffic control system” (Barney 2003).

#### 3.6.1 Group traffic control algorithms

Group traffic control systems can operate according to a number of group traffic control algorithms. A group traffic control algorithm is “a set of rules defining the traffic control policy, which is to be obeyed by the lift system, when a particular traffic condition applies” (Barney 2003). Examples of these conditions are uppeak, down peak, heavy floor demand and night service: when a certain condition applies, the control system switches to the relevant algorithm and the performance of the lift system changes to fit the (expected) passenger demand.

#### 3.6.2 Landing call allocation

A proper distribution of the lifts will enhance the service, and it is more efficient if only one lift reacts to a landing call. Landing call allocation “is the procedure by which a lift is assigned to service a particular landing call and prevents others from starting to move, or continuing their travel, in response to that landing call” (Barney 2003).

A common method used to allocate landing calls is by grouping the landing calls into sectors within each building zone and allocating lifts to each sector (Barney 2003). Sectoring can be divided into two main methods: static and dynamic sectoring. With static sectoring, a fixed number of landings are grouped together to constitute a sector. With dynamic sectoring, the number of floors belonging to a sector is variable and depends on the position of idle and moving cars (Barney 2003).

Group traffic systems are becoming increasingly advanced, using Artificial Intelligence (AI) techniques to ‘learn’ the behaviour of the building occupants and anticipate passenger demand.
International development in regards to, for instance, the integration of lifts for evacuation purposes need to be placed within the perspective of the experts involved, for an important part in regard to their nationality. A country’s building legislations and its traditions and customs in the building industry have a significant influence on an expert’s trail of thought.

This chapter offers a bird’s eye view of the way the building legislation and standardisation take place in a number of countries. Especially the Dutch building legislation and guidelines influence a large number of parameters and decisions: this chapter can provide more background in order to understand these decisions and to understand how the Dutch legislation relates to the international perspective.

Table 4.1 provides an overview of some comparable norms, guidelines and literature for a number of countries. Note that the compared documents may contain completely different, even conflicting conclusions, even though they address the same topics.

<table>
<thead>
<tr>
<th>Building legislation</th>
<th>European Union</th>
<th>United Kingdom</th>
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<td>The Building Regulations, Approved Documents</td>
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Table 4.1: overview of comparable legislation and standards

4.1 Dutch building code and standards

The Dutch Building Code, or Bouwbesluit, contains the requirements for all buildings in the Netherlands. An article of this Bouwbesluit typically contains 4 key parts: the subject, a functional demand, one or more boundary values and the officially recognized method of validation. For example: section 2.2, article 2.9, lid 1 of the Bouwbesluit (Period of time before collapse) states: “The ultimate limit state of a building construction of which collapse renders a smoke-free escape route unfit for use (subject), will not be surpassed for the duration of (functional demand) at least 30 minutes (boundary value) while taking into account the extraordinary load combinations that can occur during a fire, as defined according to NEN 6702 (official method of validation).”

The Dutch Institute for Standardization and Normalisation (NEN) constructs many of the official norms upon which Dutch building legislation is based. This includes supervising
the validation of these norms by tests, where necessary. As can be seen in the example above, the Dutch Building Code often refers to these norms for the details of the validation methods that an engineer is required to confirm for his design.

Besides the Bouwbesluit, the Dutch government also officially recognises a number of guidelines and technical agreements: these options don’t hold the same legislative weight as the official building code, but they do have a number of advantages. One important example is the Nederlandse Praktijkrichtlijn (NPR), or roughly translated the “National Guideline”. Another possibility are “technical agreements”, in Dutch Nederlands Technische Afspraken or NTA’s. NTA’s are comparable to the ISO’s “Industry Technical Agreement” (ITA) and is a medium in which specifications can be registered in a relatively short time and without too much hassle and bureaucracy. The drawback of this method is that an NTA is a trade agreement upheld on a voluntary basis by participating companies and therefore cannot be enforced by law. Nevertheless, an NTA provides the Dutch (building) industry with fast procedures and, in time, NTA’s can be upgraded to official norms.

4.1.1 Limitations and the Equality Based Principle

The Dutch Bouwbesluit is only applicable for buildings that do not exceed 70 meters in height. The reasoning behind this specific height is the requirement that a building needs to be evacuated within 20 minutes (for buildings between 50m and 70m, Toelichting Regeling Bouwbesluit 2006). When assuming an average floor height of 3.5m and an average evacuation speed of 1 minute per floor, the maximum height allowed for a building therefore becomes 20*3.5= 70 meters. Up until 10-20 years ago, buildings that exceeded 70 meters were considered to be exceptional: the safety of these exceptions could be regulated by applying the Equality Based Principle for all buildings exceeding a height of 70m.

The Equality Based Principle (Dutch: Gelijkwaardigheidsbepaling) is explained in paragraph 1.1, art. 1.5 of the Bouwbesluit and states that the requesting party needs an exemption by the local authorities after showing that the building provides at least the same measure of protection and safety that has been demanded by the current demand in the relevant articles of the Building Code.

The Equality Based Principle is a general term that the Bouwbesluit uses regularly to cover issues that aren’t specifically addressed. Buildings with a height >70m are an example, but also fire suppression systems like sprinklers are examples of equality-based safety measures.

4.1.2 Guidelines for buildings higher than 70m

Due to the Equality Based Principle, the requirements that tall buildings needed to meet were sketchy and open to interpretation. Once more and more buildings exceeded this height, the Dutch building industry collectively started voicing their concerns and requesting more specific requirements for tall buildings. A main reason for this request was the fact that local authorities regularly reject designs because they “aren’t sufficient”, wasting many work hours that the building company had invested into that design. This is often due to the arbitrary nature of evaluation methods used by the local authorities, and designs that were originally approved can be rejected at completion of the building 1-2 years later. This means that the Dutch building industry has a lot to gain financially with clear, unambiguous building legislations.

The Bouwbesluit itself hasn’t been changed yet, but there is a guideline for buildings higher than 70 meters. This guideline was created by the SBR (2005), a Dutch research foundation and focuses mainly on fire safety of buildings higher than 70 meters.

A recent initiative is the “Convenant Hoogbouw”, a cooperation coordinated by the Dutch NEN. Many Dutch companies in good standing take part in this cooperation effort, which
aims to create NTA’s for buildings above 70 meters. Design NTA’s in several fields of expertise are being compiled, covering all aspects of building design. This will provide a significant expansion of general standards that designers can refer to in the Netherlands.

4.2 British building code and standards

The British building code can be defined as followed: “Building regulations, which are made under powers provided in the Building Act 1984 and apply in England and Wales, are mainly found in The Building Regulations 2000 (as amended) and The Building (Approved Inspectors) Regulations 2000 (as amended). The legislation covers both the technical standards that need to be met and the procedures that need to be followed.”

Practical guidance on ways to comply with the functional requirements in the Building Regulations is outlined in a series of ’Approved Documents’ published by Communities and Local Government. Each document contains:
- General guidance on the performance expected of materials and building work in order to comply with each of the requirements of the Building Regulations;
- Practical examples and solutions on how to achieve compliance for some of the more common building situations.

BSI British Standards is the UK’s National Standards Body (NSB) and was the world's first. Part of BSI Group, BSI British Standards has a close working relationship with the UK government, primarily through the Department for Innovation, University and Skills (DIUS). The British Standards (denoted as “BS [number]:[year of publication]”) are the British equivalent of the Dutch NEN. The standards still under development are termed “Preliminary Documents”. These documents are denoted as “PD [number]:[year of publication]”.

The British building code describes the requirements for evacuation lifts in Approved Document B – Volume 2 – Buildings other than dwellinghouses (p. 59). It states that: “…in some circumstances a lift may be provided as part of a management plan for evacuating people. In such cases the lift installation may need to be appropriately sited and protected and may need to contain a number of safety features that are intended to insure that the lift remains usable for evacuation purposes during the fire. Guidance on the design and use of evacuation lifts is given in BS 5588-8:1999”.

4.3 European code and standards

One of the main reasons for countries in the European union to adopt uniform standards, rules and regulations is to remove trade barriers between the member countries. For example: a door manufacturer in Poland can produce doors with a fire rating using verification methods that have been accepted in all EU countries.

Where a conflict arises between EC (European Community-first pillar) law and the law of a Member State, EC law takes precedence, so that the law of a Member State must be disapplied. This doctrine, known as the supremacy of EC law, emerged from the European Court of Justice in the legal case of Costa vs. ENEL (Case 6/64 1964). It should be noted however that (the Supreme Courts of) several Member States have added specific conditions to this doctrine in order to ensure their sovereignty. Furthermore, many countries add additional requirements to certain EU codes.

1 Source: http://www.communities.gov.uk/planningandbuilding/buildingregulations
preferring their own (more strict and/or detailed) national approach, and many national building codes cover topics that aren’t covered (yet) by EC law.

European building codes are denoted as “EC [number]”. Like the Dutch NEN norms and the British Standards, The European Union has adopted EN standards, denoted as “EN [number]”.

EN 81-72 describes the requirements for fire-fighter’s lifts, including safety features like a protected lobby. The European code states however that fire-fighter’s lifts cannot be used yet to evacuate civilians, because information on this subject is not yet sufficient.

4.4 United States of America; codes and standards

Up until 1994 the United States had three major non-profit organisations developing building codes for the governing of building constructions: the Building Officials and Code Administrators International, Inc. (BOCA), the International Conference of Building Officials (ICBO), and the Southern Building Code Congress International, Inc. (SBCCI). In 1994 these organisations merged to form the International Code Council (ICC). ICC publishes the International Building Code (IBC), used by most of the jurisdictions within the United States. The first edition of the IBC was published in 2000. Contrary to what its name suggests, the IBC is not implemented by the entire world but primarily by the U.S.A.

The building codes rely heavily on referenced standards published by other standards organisations as the National Institute of Standards and Technology (NIST), the American National Standards Institute (ANSI), and the National Fire Protection Association (NFPA). The structural provisions rely heavily on referenced standards, especially the Minimum Design Loads for Buildings and Structures published by the American Society of Civil Engineers (ASCE-7).

The 2009 NFPA 5000: Building Construction and Safety Code is a very recent document that includes requirements regarding lift use for occupant-controlled evacuation and dedicated lifts for the emergency services.

4.5 International legislation and standards

Arguably the most well-known organisation regarding the promotion of international standards is the International Organization for Standardization (ISO). ISO is a network of the national standards institutes of 162 countries, one member per country, with a Central Secretariat in Geneva, Switzerland, that coordinates the system.

ISO standards are the base for many globally implemented things like ISBN numbers in books or credit card specifications. There are a large number of ISO standards related to the building industry as well.

ISO/TR 16738:2009 provides information on the engineering methods available for evacuation strategies; information is presented on the evaluation, quantification and management of occupant behaviour (particularly escape behaviour) during a fire emergency. It does not however include use of lifts (elevators) in emergency evacuations. ISO/TR 16765:2003 provides a comparison of worldwide safety standards on lifts for fire-fighters. ISO/TR 25743:2010 investigates and highlights the main risks associated with using lifts (elevators) for the evacuation of persons in various types of emergency. This study, conducted by ISO/Technical Committee (TC) 178, is still under development.
This chapter describes how fire safety design influences the building design in general. The current building practice is the benchmark from which the questions need to be asked how lifts can be integrated into the evacuation process, and which of the current safety measures and protocols need improvement.

Understanding the traditional fire safety design helps to clarify the potential threats and risks surrounding the use of lifts for evacuation, as well as the concerns voiced by building officials, emergency services and governmental institutes. Chapter 6 will describe these threats and concerns more specifically.

5.1 Introduction

A lot of attention will be devoted to fire safety in particular, as this threat has a relatively large impact on building design. Naturally, fire isn’t the only possible threat for a building’s occupants: natural disasters like earthquakes, hurricanes and other extreme weather conditions can be cause for additional safety measures. Not all of these threats are relevant however, when considering the scope of this thesis project.

The Netherlands are rarely subjected to earthquakes, hurricanes or sand storms. The risk of a flood may be thought to be larger in the Netherlands than in other parts of the world: however, the extensive safety requirements and protocols issued by the Dutch government reduce the actual risk of flood (or at least being surprised by one) to a minimum.

Whether in case of a flood or a terrorist attack, some preventive measures can be made in the design, but both examples are generally accepted to be rare events. If such an event does indeed occur, it would result in extreme damage against which it is impossible to design a guaranteed “failsafe” construction. Designers can reduce the risk of progressive collapse of the load bearing structure, but the amount of safety factors and secondary load paths needs to be limited at some point, in order to achieve a feasible design.

In order to retain the focus of this thesis project, the safety measures for these ‘extreme’ threats will be contained to (precautionary) evacuation.

5.2 Compartment fires: basic definitions

It is vital to understand how a fire behaves before one can even begin to think about fire safety design. Many might consider this to be an obvious statement, but traditional European fire safety engineering suggests that (fire) legislation isn’t necessarily the sole result of rational thinking.

Fires can show enormous differences in behaviour, but the compartment fire is a concept that is often referred to. Compartment fires are defined as “fires in enclosed spaces, which are commonly thought of as rooms in buildings” (DiNenno 1995). An idealised compartment fire, as shown in figure 5.1, has the following growth stages:

![Figure 5.1: development of a typical compartment fire](image)
1. Ignition stage
2. Growth stage (figure 5.1, A)
3. Flash-over
4. Fully developed fire (B)
5. Decay (C)

Note that safety measures are available for every one of these stages. The ignition stage is the period during which the fire begins. If the temperature, the amount of fuel and the amount of oxygen are sufficient (also known as the “fire triangle”), the fire can grow and spread. During this growth stage, the smoke and heat generated by the fire will rise to the ceiling of the compartment and accumulate. Because of the relatively small ventilation openings in the enclosed space, the accumulating energy causes the temperature in the top gas layer to rise.

When exposed to enough radiation, combustible objects will ignite, even without the presence of an open flame. The regulated conditions for this to occur can differ between countries; in the Netherlands for instance, cellulose-based products (wood, paper) are assumed to ignite at a radiative flux of 15 kW/m² (NEN 6069). The hot gasses and smoke reach this level of radiation at a temperature of 500°C, which means that this temperature will cause a violent transition in which all combustible items in the compartment become involved in the fire. This transition is called flash-over: it generally is assumed to occur at temperatures of 500-600°C (DiNenno 1995).

Flash-over induces the next stage, known as a fully developed fire. The heat release rate of the fire is now at its highest. Before flash-over a fire’s heat release rate is primarily determined by the amount and type of fuel: this is known as a fuel-controlled fire. When fully developed, the heat release is typically limited by the amount of oxygen available, also known as a ventilation-controlled fire. This also means that a ventilation-controlled fire lasts longer if the supply of oxygen is reduced: therefore the surrounding structure is subjected to lower temperatures, but over a longer period of time.

Once the fuel inside the compartment has been depleted enough, the amount of oxygen ceases to be the bottleneck, making the fire fuel-controlled again. Temperatures will steadily drop until the fuel is fully depleted, and the fire dies out.

5.3 Fire safety measures

Fire safety design isn’t confined to evacuation alone: it can be found through all stages of a (potential) fire. The following steps can be discerned: Prevention, Compartmentalisation, Structural Integrity, Detection, Information, Evacuation, Suppression, Repression and Recovery. Each of these stages influences the design of a building and will be discussed in further detail.

5.3.1 Prevention

The first step towards creating a safer building is ‘simply’ the reduction of the amount and the surface area of combustible materials. Minimizing the Fire Load Density inside certain compartments, using materials that have better characteristics in terms of combustibility and applying fire-retardant coatings are all examples of fire prevention. Section 2.11 of the Dutch Building Code describes the legal requirements in respect to reducing fire hazards. The Dutch norms NEN 6064, NEN 6065 and NEN 1775 describe the requirements concerning combustibility and flame/smoke propagation in detail.

The ‘simplicity’ of this statement can be easily overestimated. The differences between designed materials and the materials actually used during construction may differ, the quality of the applied maintenance may result in a deteriorated state of materials and coatings, and the functions of compartments or even entire buildings are likely to change.
as the years pass by. Company archives/libraries have a different fire load density compared to a ‘regular’ office room. Hotels prefer their main lobby areas to be luxurious, with thick carpets, upholstered furniture and lavishly decorated wallpaper.

History has proven that the paradox of a main entrance (lobby) area to be both a company’s calling card and a key area in case of evacuation, can lead to catastrophic events. One of the most infamous examples is the MGM Grand fire in Las Vegas on November 21, 1980. The probable cause was an electrical ground fault in The Deli, a restaurant (Best et al. 1982). Once the fire spread out into the casino area on the second floor, fire propagation and smoke accumulation occurred at an extremely fast rate. The plastic mirrored plastic ceiling panels, wallpaper and (plastic covered) furniture, combined with the very large, undivided area of the casino caused the fire to race through the area at a rate of 4-6 meters per second. The force of this firestorm literally “blew out” the doors to the porte cochere, involving this area in the fire as well (see figure 5.2).

According to eyewitness reports, smoke levels increased dramatically within seconds (Best et al. 1982). Smoke was the cause for the death of the majority of the 85 casualties. The MGM Grand fire is a tragic example of how the choices concerning material usage can severely affect the fire safety.

5.3.2 Compartmentalisation

Compartmentalisation is a tactic that relies on the ability to confine a fully developed fire to a part of the building, i.e. a fire compartment (DiNenno 1995). The barrier is supposed to be sufficiently fire resistant to allow the compartment to burn itself out: in other words, the needed fire resistance depends on the Fire Load Density of the combined materials inside the compartment. During this time, the barrier should prevent both fire propagation and smoke spread to other compartments. Compartmentalisation requirements are described in section 2.13 of the Dutch Building Code.
An important note is that with fire compartmentalisation, the prevention of smoke spread is arguably more important than flame spread. Smoke is the main “killer” during fires, and preventing/reducing smoke spread is much more complicated than one might think. Figures 5.2 and 5.3 illustrate how much the smoke could spread to the high-rise section of the MGM Grand, even though it wasn’t directly involved in the fire. If the casino had been properly designed (and maintained), the smoke plumes pouring out of the high-rise section (see figure 5.3) shouldn’t have existed. Sections 2.15 and 2.16 of the Dutch Building Code describe the requirements regarding smoke development and smoke spread.

A truly sufficient fire barrier is more difficult to realise than one would think, and the reliability of compartmentalisation can vary (see table 5.1). One of the main reasons that fire barriers fail is the lack of attention for every possible breach, due to for instance ventilation ducts and electrical wiring. Due attention isn’t only necessary during the design and construction phases, but also throughout the following years, as proper maintenance should keep the reliability of (for instance) fire flaps in ventilation ducts and other safety measures acceptable. In addition, any remodelling of building sections should be done with great care, maintaining the integrity of the fire barrier.

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Table 5.1: Published estimates for fire protection systems (probability of success in %) (Bukowski et al. 1999)

When emphasising the border between a starting fire and a fully developed fire (also known as a post flash-over fire), so-called “passive measures” like compartmentalisation and preventing progressive collapse should arguably be placed behind “active measures” like detection and suppression. However, Dutch building codes still place the main emphasis on passive fire measures. Active safety measures can be implemented through the “Equality Based Principle”, which is explained in more detail in section 4.1.1.

Again, the MGM Grand Hotel fire proved how disastrous the consequences of a poor design may be. The lack of adequate sprinklers and fire barriers allowed the (fully developed) fire and smoke to spread from The Deli to the casino area (Best et al. 1982). More disastrous however were the insufficient measures to prevent, in particular, the thick smoke from spreading into the high-rise tower. According to the official investigation report by the NFPA (1982), “several unprotected vertical openings and vertical openings with enclosure deficiencies allowed the spread of smoke and heat to the high-rise tower. These vertical openings included seismic joints, interior stairways.
and smoke proof stair enclosures, toilet exhaust shafts, and other building penetrations such as pipe chases.

In addition, the ventilation system remained functional during the fire (!), sending smoke-filled air into the hotel rooms. In a number of rooms casualties were found while the rooms didn’t show any signs of smoke or fire; after further investigation it was determined that the filters in the air vents filtered out the smoke particles. The toxic gasses like carbon monoxide were still being pumped into these rooms however: with no apparent signs that they were slowly being poisoned, the room occupants grew tired as they were waiting to be rescued, then died of asphyxiation.

5.3.3 Structural integrity

Like compartmentalisation, the preservation of structural integrity is a passive safety measure. Section 2.2 of the Dutch Building Code requires the load-bearing structure to resist progressive collapse for a minimum time period, depending on the category of that building. A building category is based on a building’s height and its function (residential, commercial, storage etcetera). The Dutch norm NEN 6068 describes the conditions for fire propagation due to flash-over, the required resistance against flash-over and desired resistance of fire compartments. The Dutch norms NEN6071, NEN6072, NEN6073 and NEN6069 describe the resistance against structural failure of concrete, steel, wood and other materials.

Figure 5.5: required structural fire resistance for non-residential buildings (Bouwbesluit afd. 2.2, NEN 6702)
The overview depicted in Figure 5.5 shows the Dutch Building Code requirements for new, non-residential buildings, like warehouses, stores, hotels and office buildings. The requirements for residential or existing buildings (i.e. buildings built before this legislation was valid) are different. This overview clearly shows how the requirements are based on the combination of a building’s height and its function (and to some extent on the fire load density). The principles of Dutch legislation are explained in more detail in paragraph 4.1.

5.3.4 Detection

Detection is one of the possible “active measures” in fire safety engineering. With a proper detection system it is possible to detect a fire in an early (pre flash-over) stage and intervene before flash-over occurs. This can significantly decrease the extent of the direct damage dealt by the fire and the indirect damage due to delays in activities. Figure 5.6 shows the (natural) temperature development of a typical compartment fire: the effects of early detection and suppression are quite clear.

The value of a detection system depends entirely on the information it relays (what, where, to whom?). Combined with alarm and fire control systems, it decreases evacuation times and fire/smoke damage. If linked to the fire control panel (often found in large buildings) it can provide the fire department with a host of valuable data.

Many of the current (optical) detection systems in use have an important drawback: due to poor maintenance these detectors are triggered by accumulated dust particles, resulting in a false alarm. Between 80%-98% of all fire alarms in the Netherlands are false: advanced detection systems are able to, for instance, monitor their signal history (adapting alarm criterion to dirt, environmental conditions etc.): these systems can save a lot of money and frustration.

5.3.5 Suppression

Suppression, like detection, is an active measure. Sprinklers are an example of fire suppression systems. When a developing fire triggers a suppression system’s sensors, the system activates. The design strategy can aim to control the fire or even distinguish it. In any case, suppression systems aim to prevent a developing fire from reaching the flash-over stage. The effect of sprinklers has been illustrated in figure 5.6.

A common misconception is that sprinklers cause a lot of collateral damage. Fact is that only a limited number of sprinkler heads activate and that the early response limits both fire damage and smoke damage, if the system functions properly. Again, proper maintenance is of key importance.

Another common misconception is that passive safety measures are by definition more reliable than active safety measures. The cause of this attitude is most likely the notion that, in case of an “active” measure, a system needs to be activated. This sounds as if these measures are more prone to malfunction than a “passive” measure: after all, how could a wall malfunction? Empirical evidence like the data provided in Table 5.1 shows however that sprinkler activation is actually more reliable than compartmentalisation. Like explained in 5.2.2, the reason for this is that constructing and maintaining a proper fire barrier is much more difficult than it seems.
There are examples of disasters where the sprinkler installation failed. An example is the collapse of WTC tower 7 on September 11, 2001 (NIST 2008). In the case of WTC 7, falling debris from WTC tower 1 caused fires to start in tower 7. The 47 story high office building burned for almost seven hours before the fires caused a progressive collapse of the entire building. The collapse of towers 1 and 2 had damaged the water supply, rendering the sprinkler system useless. Although the 9/11 disaster should be categorized as an extraordinary event, it does prove the possibility that active measures can fail, and that a fire can cause a progressive collapse.

5.3.6 Information and communication
The importance of information handling isn’t emphasized that much in ‘traditional’ fire safety design. However, a systematic approach to file information from (for instance) smoke and temperature sensors, activate fire control systems and relay & display it to the relevant parties is essential, especially in the case of high-rise buildings with many occupants and relatively large and complex installations.

The first and foremost reason for an information system is to alarm the building occupants (evacuation) and the fire department (providing emergency response, aid, crowd control and fire attack). In some cases, the evacuation process requires a “silent alarm”, giving the appointed safety personnel the time to take their positions before the host of the building occupants are informed. This can prove to be very beneficial in high-rise buildings: having key personnel on-site at the important traffic nodes in time should vastly improve the evacuation process, especially in regard to the ability to direct pedestrian traffic flows into the right direction (routing) and provide building occupants with information, assistance and reassurance.

Information isn’t limited to a fire alarm (Light & sound, slow-whoop, spoken text), but it is also essential for proper direction to safety via the designated evacuation routes. Signs, arrows, fluorescent routing strips, directions via intercoms and information displayed on
monitors are all examples of information supply to guide building occupants to the designated secure areas.

Finally, information can be of vital importance for the fire department. A fire control panel, situated at the main entrance lobby or in the building security area, can form the heart of the coordination centre of the designated safety personnel and later the fire department. The fire control panel can display and keep track of the location of the fire (activated sprinkler heads) and possibly the condition of the area of the fire and the surrounding areas (smoke detectors, security cameras). It can display the status of installations (HVAC, elevators, (backup) power, pressurization of stairways, water supply), and possible malfunctions. Information in the form of direct communication can be provided via secure intercoms. All-in-all, fire control panels can provide information from a remote location about every part of the building, which allows for better preparation and for a shorter and well-informed decision making process.

The examples above show that information and communication go hand in hand. Information monitors also provide a medium for real-time updates and messages. The Fire Command Station (FCS) is the ultimate place for building officials and emergency services to convene and decide their course of action, based upon the information available to them. Monitors and two-way intercoms at important locations like protected lobbies and rendezvous floors facilitate the teams on those locations with a lifeline to the command centre. While simple, unambiguous protocols should keep the tasks of all ASS teams and professional response teams clear, any confusion can be solved directly by contacting the FCS. The teams can keep themselves informed of the status in other areas of the building. Armed with this knowledge, ASS teams and emergency personnel can assist the building occupants and their concerns better and with more confidence, reinforcing their position as authority figures. Additionally, fire control panels and/or information monitors can help to reduce the high volume of radio traffic between the emergency response teams at the different locations.

5.3.7 Evacuation
Evacuation is one of the main stages of the fire safety measures. This stage is the main focal point of this thesis. A general description is given in section 5.4.

5.3.8 Repression and recovery
Repression is the stage where the fire department decides to attack the fire and/or takes measures to prevent spreading of the fire to other compartments and nearby buildings. As emphasised in section 5.3.6, all available information can vastly improve the efficiency and safety of the personnel at the scene. In addition, it is vital that any necessary building services (like dry risers or standpipes, emergency stairways and fire lifts) are safe, readily available and easily accessible.

During the Recovery phase, the main goal is to restore the affected area to its previous state. Recovery efforts are concerned with issues and decisions that must be made after immediate needs are addressed. Recovery efforts are primarily concerned with actions that involve rebuilding destroyed property, re-employment et cetera (Haddow et al. 2004).

5.4 The phases of incident response and evacuation
The general procedure in response to an incident can be divided into a number of stages. It is important to recognise the differences between the procedure followed by the building occupants and by the emergency response services.
5.4.1 General description

In this case a fire is used to describe the different stages of incident response and occupant evacuation. After a fire starts, it takes some time to actually determine that something is wrong: this is known as the detection time. Detection can be made manually by people observing fire or smoke in the area or automatically via smoke/heat detectors or sprinkler heads. Detection should trigger the emergency protocol system, alerting the building security staff and (possibly after a delay) occupants of the building that a fire condition has been detected and what actions they should take. Simultaneously the local fire department receives an automated alarm (which means that the notification time is more or less the same as the detection time).

![Diagram of emergency response procedure](image)

Figure 5.7: Emergency response procedure diagrams for building occupants and emergency response services.

After the alarm has been sounded, ASS teams need to organise themselves and the building occupants typically need a few minutes to understand what is going on: this period of time is known as the reaction time. A quick reaction time is extremely important but can vary in reliability, as it is heavily dependant on experience through fire drills, the capabilities of the Appointed Safety Supervisors and the quality of the emergency notification/information system.

During the evacuation stage the building’s occupants leave their floor via a protected exit path, by which they can either leave the building or relocate to a refuge area inside the building. Note that the (vertical) egress time is only part of the evacuation time, which also encompasses the necessary time to exit the building and reach the appointed rally area outside.

For the emergency response services, the response time is the time needed to prepare themselves and travel to the scene of the fire. After a proper assessment of the situation and the necessary preparations, emergency response teams set out to provide the necessary assistance to the building occupants (evacuation assistance, search & rescue, first aid treatment), and make their approach towards the incident location to control and/or extinguish the fire (repression).

5.4.2 Official legislation and guidelines regarding time frames

The detection and response phases are widely recognised and the Dutch building code (2003) has determined the requirements for the maximum length of these time frames.
In order to determine the egress time, the widely known “1 minute per floor”-rule has been used, assuming that evacuees take 1 minute to descend 1 floor via the emergency stairwells. Assuming a floor height of 3,2 meters, this amounts up to 15 floors above ground level (51m). For 70 meters, this would amount to 21 floors above ground level. The SBR guideline (2005) has adopted time frames based on the legal requirements.

Table 5.2 shows the required time frames for each phase of detection and response. It includes adopted time frames used by other countries and organisations, for comparison.

<table>
<thead>
<tr>
<th></th>
<th>Bouwbesluit</th>
<th>SBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection time</td>
<td>13 min.</td>
<td>13 min. (possible reduction to 5 min. with proper detection)</td>
</tr>
<tr>
<td>Reaction time</td>
<td>2 min.</td>
<td>2 min.</td>
</tr>
<tr>
<td>Travel time to emergency stairwell</td>
<td>60 s.</td>
<td>60 s.</td>
</tr>
<tr>
<td>Maximum evacuation time (building height &lt; 50 m)</td>
<td>15 min.</td>
<td>~</td>
</tr>
<tr>
<td>Maximum evacuation time (50 m &lt; building height &lt; 70 m)</td>
<td>20 min.</td>
<td>~</td>
</tr>
<tr>
<td>Maximum evacuation time (building height &gt; 70 m)</td>
<td>~</td>
<td>max. 60 min. after initiation fire</td>
</tr>
<tr>
<td>Response time fire department</td>
<td>~</td>
<td>8 min.</td>
</tr>
</tbody>
</table>

Table 5.2: official requirements for time frames for detection & response phases

The SBR guideline for these time frames will be used in calculations:
- Detection time: $T_{\text{detection}} = 13$ minutes; 5 minutes with a full fire detection system
- Reaction time: $T_{\text{reaction}} = 2$ minutes
- Pedestrian travel time to the emergency stairwell: $T_{\text{initial}} = 60$ seconds

5.4.3 ‘Defend-in-place’ strategy
A well-known international strategy for fires in high-rise buildings is the defend-in-place principle (Cote et al. 1988). Instead of evacuating the entire building, only the incident location and the surrounding floors are cleared of building occupants. These people are directed either out of the building or to an area of refuge. After the fire department has resolved the incident, they decide whether it is safe to return to the evacuated zone or if the affected area isn’t safe enough to re-enter.

It is possible that the fire department decides to shift their strategy from defend-in-place to total building evacuation, if they decide that the safety of the building occupants in the rest of the building cannot remain guaranteed.

5.5 Human behaviour during emergencies

Human behaviour is one of the most important and difficult issues to factor in when designing safety measures: how do people respond to an emergency? Will they interpret the information and directions that you have designed for them correctly? Will the fire escape routes you design be used as you intended? The subject of human behaviour is too broad and too complex to discuss in full detail: therefore only a few topics of frequent discussion will be mentioned in this section.

5.5.1 Stress versus panic
When confronted with an emergency situation, people will understandably experience an increased amount of stress due to the prospect of danger, the limited amount of time to make decisions as well as the limited and ambiguous information available (Proulx 2002). In debates concerning emergency evacuation, the risk of panic is mentioned regularly: in fact, panic in the form of irrational behaviour is rare during fires and
researchers have long ago rejected this concept to explain human behaviour in fires (Sime 1980, Proulx 2002).

Occupants of non-residential buildings usually don’t react very quickly when the fire alarm sounds: after the question “Another drill?”, they finish the sentence of the document they were writing, have a little chat as they sidle off towards the emergency stairwell and realize only later on that there was an actual emergency. In some cases of residential apartment fires, neighbouring occupants have been known to actually watch the fire from the balconies of their own apartments. This lethargic response significantly increases evacuation delay times.

There are a few notorious examples where mass panic did indeed cause additional casualties. The Hillsborough disaster of April 15, 1989 at Sheffield, England is described in the Taylor Report (1990). In the time preceding and during a football match Hillsborough Stadium, the crowd waiting in the area before the turnstile entrances became increasingly anxious to watch the game, particularly when they heard the starting signal. In order to relieve the pressure caused by the crowd at the entrance, additional gates were opened, causing a large influx of people through the narrow tunnels and into the already crowded stands. By the time the referee stopped the match, the situation had become uncontrollable and large numbers of football fans were being crushed against the fencing, with little or no exits to escape through. This resulted ultimately in the death of 96 people, with 766 injured and 300 hospitalised (Daily Telegraph 2009).

A Dutch example is the fire during a New Year’s celebration in a pub in Volendam. When the Christmas decorations set the entire ceiling of the second floor ablaze in under half a minute, the crowd of people upstairs had almost no time at all to react; additionally a number of fire exits were blocked. The disastrous combination of the rapidly spreading fire, the dense crowd and the confusion caused by blocked egress paths led to the horrible death of 13 people, with over 180 wounded (NRC 2001).

Both examples have the following key components that led to a situation of uncontrollable panic: a dense population, a sudden mass awareness of an obvious threat and limited, unclear egress paths. Taking measures to create wide, unobstructed and clearly visible egress paths should therefore help to minimise the chance of panic situations.

Properly trained floor wardens and real-time information supply are methods to increase awareness of gravity of the situation and thus speed up evacuation. Proulx (2002) advocates more research on alarm systems that focus more on “some specific building characteristics that could explain occupant response”, like building functions, occupant activities and the manner in which information is provided. This could help trigger the desired response from building occupants and thus keep the evacuation process under control.

5.5.2 Habits and familiarity versus designed egress paths

During an internship, the author experienced first-hand how people revert to habit when faced with, in this case, a fire drill. The building in question had two emergency stairwells: one stood fairly close to the lifts and was used by many people to reach the company restaurant at lunchtime; the other was situated at the far side of the building, outside the normal routes that people follow during normal conditions. During the drill, almost the entire building population chose to use the first stairs, even if their office was next to the second stairwell. The conclusion was that more emphasis should be made by the ASS team on the second stairwell in future evacuation drills, in order to make occupants better aware of its existence and in order to attempt to break this behavioural pattern and divide the evacuation traffic better over the two stairwells.
Decision-making under stress is often characterised by a narrowing of attention and focusing on a reduced number of options, thus a person is unlikely to develop new solutions under heightened stress (Proulx 2002). This reinforces the importance of regular evacuation drills: in addition these drills need to be properly organised, monitored and evaluated to avoid unbalanced use of the emergency egress provisions. Even better would be to incorporate the concept of habitual behaviour into the design of the emergency egress paths and provisions, for instance by situating the egress path within or directly adjacent to the regular traffic routes of a building.

5.5.3 Further research

Human behaviour is a subject in the field of fire safety engineering that is particularly difficult to define. It is also arguably the most discussed topic among experts, with many contradicting opinions. A thorough study of human behaviour is beyond the scope of this thesis: although the proposed solutions have incorporated elements this subject as much as possible, further studies are needed to provide a better understanding about the optimal methods and provisions for emergency egress.

The aspects of (individual) human behaviour have caused building safety engineers to shift their egress calculation methods from a macroscopic approach to a microscopic approach (see paragraph 9.2). Advanced computer simulation programs provide the option to assign individual characteristics to a huge amount of virtual ‘people’ and calculate the results. After running enough simulation runs by enough programs from independent sources, patterns may emerge that can be redefined into models.
Part II

In-depth research
6 LIFTS IN EMERGENCY SITUATIONS

After decades of informing the public, safety drills et cetera, it is common knowledge that lifts should not be used during a fire. A fire is the most common emergency situation, but it isn’t the only one. This chapter provides an overview of the threats and challenges that are the cause for the strict safety measures. After describing the current usage of standard and fire-fighter’s lifts, the third section lists the advantages that lifts could provide during evacuation, provided that the requirements are met to ensure the continued operability of these lifts. Finally a few examples are given of the use of lifts in emergency situations.

6.1 Potential threats in emergency situations

In order to understand the required safety features for continued lift operability, it is crucial to understand the possible threats in the case of an incident. The lift system is one of the most delicate systems in the building, which explains the strict “fail-to-safe” principal described in section 3.2.3.

By understanding the threats to and weaknesses of a lift system, it is possible to design safety features that reduce these threats to an acceptable level and provide additional protection for the vital areas. A number of suggested safety features are described in chapter 7.

6.1.1 Earthquakes

In an earthquake one of the largest threats is the possibility that the counterweight breaks loose from its guide rails and strikes the lift car. In active seismic areas lifts are equipped with seismic sensors. When these sensors are triggered, the lift system stops the lift car, moves the lift car away from the counterweight, moves towards the nearest floor, then opens the lift doors so any occupants can exit the lift (ASME 17.1).

The Netherlands are situated in a "quiet" area regarding seismic activity: the need to include earthquakes into the risk assessment is therefore minimal. Unexpected lateral movement caused by extreme weather or by an explosion might still cause problems, however: if a jolt by an explosion, for instance, causes the entire lift system to shut down, the serious question arises whether or not it is responsible to override the safety measures and reset the lift system in order to use it for evacuation. During an emergency situation, where every minute counts, a thorough check conducted by a lift specialist of all the lift shafts in a high-rise building is simply not an option.

6.1.2 Fires, smoke, hot gasses

Fires are a serious concern in regard to continued lift operability. Exposure to heat can cause lift panels to become inoperable. Lift doors may twist and/or bend, becoming an obstruction in the lift shaft. Hot gasses may significantly weaken the strength of the (steel) lift cables and harm passengers inside lift cars.

Smoke is a particularly deadly product of fire. Smoke particles can accumulate in lift systems and render them inoperable; the main concern however is the possible asphyxiation of building occupants by the smoke entering the lift shafts (and the lift cars in those shafts) and migrating to other building floors.

6.1.3 The Stack Effect

The stack effect is based on the natural law that warm air is lighter than cool air: hot air therefore tends to rise upwards and cool air tends to accumulate at the bottom of an enclosed space. Particularly in high shafts, this effect can be very strong: it is therefore important to consider the influence of the stack effect in high-rise buildings, particularly in vertical passageways like stairwells and lift shafts.
In the summer, the warmed air in a lift shaft will rise, causing an upward airflow. During the winter, the cold air will flow in the opposite direction, also known as the negative stack effect.

During a fire, an exposed vertical shaft may have disastrous consequences. The hot gasses and smoke will fuel the stack effect in the shaft, turning it into a giant chimney. In addition to sucking in fresh air into the fire, the hot gasses and smoke will rapidly migrate to other floors and spread the fire. This breach in horizontal compartmentalisation can result in multiple large, fully developed fires on many different floors in an alarmingly short period of time. Arguably even more important than fire spread would be the smoke migration into these shafts, for aforementioned reasons.

6.1.4 The Plunger Effect
An additional phenomenon in lift shafts is the “Plunger Effect”. As a lift travels up and down the shaft, it creates local overpressure and suction above and below the lift car, depending on the direction of movement. With a single lift per shaft, this can cause positive and negative airflow through the landing doors of intermediate floors, similar to the effects of a piston or plunger. In high-rise buildings with multiple lifts per shaft however, the plunger effect is not nearly as strong and therefore will not be taken into account in this thesis.

6.1.5 Structural damage and obstructions
Any structural damage to the building for any reason whatsoever can result in deformations of the building structure. As lifts (especially high-speed shuttles) need to be aligned with great precision, these deformations will cause the lifts to either become entirely inoperable or only usable at very low speeds.

Obstructions caused by structural damage, debris, deformations or other sources will obviously interfere with lift operability. One major cause for concern is the possibility that an obstruction can cause the lift car or counterweight to become damaged, stuck or get knocked out of its guide rails.

6.1.6 Power shortage
While passive elements of the emergency egress system like a flight of stairs do not need electrical to remain functional, a reliable power source is crucial for active elements like lifts. Not only the lift operability itself needs to remain intact; all the necessary support systems like lift control & monitoring, communication & information systems and lift shaft pressurisation need to remain functional. Even in stairwells, power is needed for pressurisation and basic lighting (although backup systems like batteries and photo luminescent markings are a possible option in regard to illumination).

A lift system’s dependence on electrical power is a possible liability: any power failures or short-circuits could render the lifts useless. The fire department may choose to cut the power of a building to protect their personnel while extinguishing the fire, for example.

A building’s primary power grid may be very vulnerable, dependant on its design. Even with a secondary power source like a local backup power generator, shielding/isolating the entire lift (electrical) system and ensuring its integrity is a challenging task. If only part of the lift group is required to remain functional for evacuation purposes, that part deserves due attention.
6.1.7 Water
Water leakage in general could cause a short-circuit and is therefore a potential fire hazard. With lifts, any water (from a fire hose or sprinkler for instance) that seeps through the lift doors and into the shaft could cause short-circuits or trigger the lift sensors situated at every landing. Unless a lift has been “hardened”, that lift will shut down. In case of a manual system override, dysfunctional sensors may cause lift cars to fail to locate floors: lift cars may not align well with landing floors or miss them entirely. In addition to the electrical and sensory systems, (dirty) water can affect numerous other lift components like cables, flywheels and grooves or rails.

Another complication is the accumulation of water in the lift pit. As the pit contains a number of important components, it would be necessary to extract the (dirty) water by means of a pump, for instance.

6.2 Current use of standard lifts and fire-fighter’s lifts
Where paragraph 3.2 described the general components of a lift, this paragraph specifically describes the safety measures that have been developed over time in regard to fires and other extraordinary events. Unfortunately developments in safety design have a tendency to take place after disasters have shown the hidden faults in (lift) design.

6.2.1 Current emergency procedures for standard lifts
The conventional procedure for lifts during an emergency can be summarised in one sentence: “Do not use lifts in case of an emergency!” If a lift has become immobilised, the occupants trapped inside are in considerable danger, as well as the emergency personnel who have the time-consuming task of freeing these occupants — time that they don’t have in an emergency situation like this.

For this reason a fire alarm typically triggers a recall procedure, where the lifts stop responding to hall calls, head down to the ground floor lobby, open their doors to let any occupants still inside out and shut down. If the fire is situated in the lobby where the lifts would normally head down to, the lifts stop one floor higher, in order to provide a safe exit for any occupants inside (NEN 81-58).

6.2.2 Current emergency procedures for fire-fighter’s lifts
The European Union have only recently published the code EN 81-72, which describes the requirements for fire-fighter’s lifts. This code does not yet include the possibility to evacuate building occupants using fire-fighter’s lifts. Some countries however have adopted additions to EN 81-72. In the British standards for example (BS 5500), the possibility of evacuating building occupants under supervision has been included as an option. In the Netherlands, the final building permits regarding special safety measures are given by the local authorities and fire department, on a case-by-case basis. This creates room for ‘special’ solutions. A large number of individual building projects have already incorporated fire-fighter’s lifts in different ways.

A common practice is to double the service lift as the fire-fighter’s lift. An important note is that these lifts have a larger load capacity, but that the lift speed is often slower, resulting in longer travel times. Most fire-fighter’s lifts typically have the option to be switched to a special emergency override mode: by using a key, emergency responders can then take over control of the lift, which then only responds to calls made from inside the lift car.

In the United states, the lift recall mode is better known as Phase I Recall, and the emergency override mode as Phase II. When referring to the theoretical possibility of
switching the standard lifts (whether or not protected by a lobby etc.) into evacuation mode, some experts have used the term Phase III (evacuation) mode.

6.2.3 Transportation of equipment
Parties in the building industry can be conservative regarding new developments, particularly when they involve the safety of civilians and personnel. Even with fire-fighter’s lifts, a number of fire-departments may choose to use the stairs to head up to the incident location. Once they arrive at the staging area 1-2 floors below incident level, they can use the protected lifts to transport the heavy gear required for the firemen to do their job.

6.2.4 Transportation of firemen
In addition to equipment, fire department officials may choose to allow the transportation of personnel by the fire-fighter’s lifts. It is quite possible that the emergency personnel require that these lifts need to be checked first to confirm their safety. This could be done by sending up an instrument pack or ROV (Remotely Operated Vehicle) first that measures the environmental conditions of the lift as it rises, and checks the conditions in the protected lobby of the staging area. Visual information via live video camera feeds can prove quite valuable as well.

If fire department policies require personal confirmation of the lifts’ safety by their first response team before lift usage, one should take into account the time needed to travel up to the staging area, against the flow of evacuees heading down in the emergency stairwell.

6.2.5 Possible evacuation of building occupants by the fire department
A third option is to allow the evacuation of building occupants under supervision of the fire department or even the in-house Appointed Safety Supervisors (ASS). Given the limited handling capacity of these lifts, the procedure would probably involve evacuating only a fraction of the population, focussing on those building occupants with mobility impairments. This tactic is currently being used in at least one building in the Netherlands: the Delftse Poort. The Delftse Poort is one of the test cases described in this thesis, in chapter 12.

6.3 Advantages of evacuation using ‘normal’ lifts
As lifts are the primary form of vertical transportation in a high-rise building, the possible advantages would be significant if these lifts could remain operational during an emergency situation. The requirements for continued operability are listed in section 7.2.

6.3.1 Shorter evacuation time
The first and most important advantage is that lifts could speed up the evacuation process—but only if it is regulated properly. The rule: “in case of fire, use the stairs!” is simple enough, and even then history has proven that confusion and a lack of information can actually increase the evacuation time. When adding lifts to the procedure, simplicity and consistency are key in order to benefit from lifts.

Particularly the combined handling capacity of lifts and stairs could lead to a faster evacuation time than using stairs alone. Example: if the lifts of an office building have a 5-minute handling capacity of 12.5%, all building occupants should be able to leave the building in 8*5 = 40 minutes, using lifts alone and in a ‘normal’ situation. In addition, evacuation is comparable to the evening downpeak; as explained in section 3.3.2, the shorter round trip times and increased efficiency increases the handling capacity of the lift system by as much as 50%. This roughly translates into a decrease of the evacuation time from 40 to 30 minutes when using only lifts; combining stairs and lifts would likely result in even faster evacuation times.
6.3.2 Reduction of constraints in the emergency stairwells

The main reasons reported by evacuees for the slow egress times via the stairwells in the New York World Trade Center in 2001 were: crowded stairwells, emergency responders in the stairwells and injured or disabled persons in the stairwells (NIST 2005, NCSTAR 1-7, pp. 151-152). When disregarding that in this extreme case the lifts were inoperable after the attack, these three constraints can be reduced or even removed by integrating lifts into the evacuation process.

By using the lifts for the proportion of building occupants who have difficulty traversing the stairs due to some form of physical or psychological reason, this possible constraint has been removed from the emergency stairwells. This would cause the pedestrian traffic flow down the stairs to run more smoothly for the rest of the population. This strategy, known as Fractional Evacuation, is explained in further detail in paragraph 7.1.2.

A short evacuation time (i.e. roughly under 10 to 15 minutes) means that (most) occupants have evacuated the building before the fire department arrives. If the fire department chooses to use the stairs for whatever reason (to ensure the safety of the fire-fighter’s lifts for instance), any problems with counterflow in the stairwells would be minimal. Counterflow is the situation where some people head in the opposite direction of the main pedestrian flow: this causes a local and temporary disruption of the main (egress) flow. By using the fire-fighter’s lifts the emergency responders could avoid the stairs altogether. In addition, the transportation of heavy equipment would become much easier when using lifts.

An important note is that the actual delay caused by counterflow was reported to have no significant negative influence on evacuation times in the WTC in 2001: the possible reason for this is the fact that, after having passed the obstruction, evacuees can temporarily move faster and close the gap caused by that obstruction. This means that the egress time does not change on a macroscopic level by these temporary obstructions caused by counterflow (NIST 2005, NCSTAR 1-7, pp. 151-152). Still, the perceived influence felt by the evacuees could be a reason to keep the two traffic flows separated when desired.

6.3.3 Reduction of the physical exertion by shortening the length of the descent by stairs

Even young, healthy individuals will eventually become tired after walking down a large number of stairs. A study in Leeds yielded that a significant percentage of the population (mainly elderly and mobility impaired pedestrians) wasn’t able to walk down more than 15 floors at once, and an Australian study from the 1980’s showed that 18-25% of the subjects would not be able to evacuate more than 19 floors (MacLennan et al. 2008). Since the 1980’s though, society is ageing, obesity rates are rising and an increasing amount of people work participate in social activities, despite any (temporary) physical limitations.

In buildings of 20+ floors high, it may be interesting to consider dividing the building into zones: at the bottom of every zone the evacuees exit the stairs and head down the rest of the way using lifts. This strategy, further described in section 8.1, essentially divides the building into smaller pieces. Building occupants need to travel a shorter distance via the stairs, thus reducing any influences of fatigue and keeping the reduction of the pedestrian egress flow manageable over time.
6.4 Examples of lift usage during evacuation in high-rise buildings

In a number of famous high-rise buildings, the building occupants and emergency services have had experience first-hand the advantages of using lifts during evacuation.

6.4.1 World Trade Center, attacks 2001

The data provided by the NIST investigation report of the WTC disaster in 2001 (NIST 2005) shows the potential of lifts during evacuation.

During the 16 minutes between the attacks of towers one and two, 40% of the population of WTC2 had successfully evacuated the building. The impact zone at WTC1 was at floor 91 and above; for WTC2 the impact zone was at floor 78 and above.

Even though nobody above the impact zone in WTC2 was able to head down after the impact and that WTC2 collapsed in a shorter time than WTC1, 90% of the occupants of WTC2 managed to escape the building alive versus 80% of the occupants of WTC1. The reduced loss of life in WTC2 has been accredited for a large part to the amount of people using the lifts during those first 16 minutes to head down to safety (NIST 2005, NCSTAR 1-7, p.152).

6.4.2 Petronas Towers, bomb threat 2001

The Petronas Towers have a permanent ASS team 24 hours per day, sufficient in first line response, fire attack and paramedic help until the fire department arrives. (Ariff 2003). “Special cases” like people with physical impairments are evacuated via the service lifts; casualties are evacuated using the fire-fighter’s lifts, of which there are two in each tower.

The towers are divided into four zones: the Low Zone (level G – 37), the Middle Zone (level 40-60), the High Zone (level 61 – 77) and the Top Zone (level 78 – 86). The occupants of the bottom zone use the stairs to head down to the ground floor. The middle zone occupants head down to level 41, where they assemble and use the shuttle lifts to head further down; The high and top zone head down to level 42, assemble and use the shuttles downwards. In other words, the building occupants of the middle and high zones are divided among the two skylobby levels at 41 and 42.

Prior to the 9/11 attacks, the strategy was to have the building occupants of the affected building cross the sky bridge situated at levels 41 and 42, then head down via the shuttles of the “safe” tower. Since 9/11 the strategy has been altered however to allow occupants to use the lifts of their own tower, in case both towers need evacuation or if the sky bridge has become unusable.

A bomb threat in 2001 showed the potential risks of the original evacuation design when occupants crowded the sky bridge in their attempts to reach the other tower. This resulted in an evacuation time of several hours (Bukowski 2008). The new plan proved to be sufficient after conducting a total evacuation drill in October 2002, where the total evacuation time clocked at 32 minutes (Ariff 2003).
6.4.3 Taipei 101, evacuation drills

Taipei 101 is 508 m in height, with 101 floors above ground and 5 underground (with the highest occupied floor at 438 m). There are over 10,000 people working in Taipei 101 or visiting every day and approximately 40,000 people enter and leave the Mall on the 4th floor on a daily basis. With such crowd capacity, safety is of paramount concern.

Since beginning of construction, fire prevention plans and emergency reaction Standard Operating Procedures (SOPs) have been developed according to the building’s characteristics. The complex has been equipped with very early warning fire detection (VEWFD) systems, smoke detection and control systems and fire-extinguishing systems. Upon confirmation of a fire by infrared detectors and cameras, large volumes of water can be discharged to extinguish the fire.

Two sets of emergency stairways allow people in the mid to lower tower to escape; air pressure is automatically controlled to minimize smoke intrusion. Refuge areas have been located every 8 floors, providing relief and temporary shelter for escaping personnel. This robust system of refuge floors provides the option to evacuate one building zone and apply the ‘defend in place’ strategy used in many mega high-rise buildings.

The building officials of Taipei 101 weren’t content with refuge floors alone: they additionally required an acceptable evacuation time in case of a total building evacuation scenario. An evacuation drill performed prior to the opening of the building yielded a total evacuation time of about 2.5 hours. After safety officials expressed their concerns, protected lifts were introduced to aid in the emergency egress from the upper levels: this reduced the evacuation time from 2.5 hours to 57 minutes (Hsiung et al. 2006).

Taipei 101 has 2 emergency rescue elevators; travelling at speeds of 480 meters per minute, it takes them only 50 seconds to climb from the 1st to the 90th floor, ensuring emergency personnel arriving within the shortest time possible.

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1 Source: www.taipei-101.com
ADOPTED SUGGESTIONS FOR EVACUATION USING LIFTS

Throughout the years, many experts have expressed their views on what they believe to be important during building evacuation. Many publications and even official guidelines can be find containing the most safe and effective methods and physical requirements for emergency egress. For this reason the following chapter will primarily describe the many existing strategies. There is however some room to offer additional thoughts about the different subjects and add a few variations to the ‘main’ strategies.

7.1 Evacuation methods when using lifts

In the Emergency Evacuation Elevator Systems Guideline (2004) the CTBUH discerns three generic emergency evacuation types: total evacuation, zoned evacuation and fractional evacuation. Note that the CTBUH refers to zoned evacuation as “staged” evacuation. Here the term “zoned” evacuation has been chosen to emphasize the fact that zoned evacuation refers to a physical location, not a moment in time or “stage”. These types have been sorted in more detail in chapter 8.

7.1.1 Zoned evacuation

In modern high-rise buildings, the complete evacuation of a building is an unlikely event: during a ‘normal’ fire, for instance, the general consensus is that zoned evacuation is sufficient, in combination with a ‘defend-in-place’ strategy. A building can be divided into a number of zones, in this case separated in fire compartments. Relocation of occupants away from the area of the incident and to protected areas of the building (areas of refuge as defined in most building codes) is the primary goal.

This method of evacuation forms the basic philosophy of egress in high-rise structures and hospitals today. Especially in buildings containing large numbers of people, zoned evacuation puts less strain on the internal infrastructure than a total evacuation would. It also prevents unnecessary disruption of the activities in other parts of the building that aren't affected by the incident. A crucial prerequisite is that the fire compartments have been properly designed and that their quality remains intact during the years that the building is in use.

The role of lifts to assist in achieving zoned evacuation is not as crucial as in the case of total evacuation: the limited amount of people to be evacuated will not cause as much congestion in the stairwells, therefore decreasing the advantage of using lifts. Lifts still can be a valuable asset during zoned evacuation, especially if the evacuation zone is relatively large or has a particularly large population (restaurants).

Defining the evacuation zone

The affected zone of the building should quickly be identified in order to ensure that building systems respond properly. If one or more elevators are used for the evacuation process, it is important to determine which elevators will be assigned for this task and how this information will be displayed towards the evacuees. In addition, occupants of the floors above and below the evacuation area should likely be informed of the situation, especially if a part of the local elevator banks ceases to respond to hall calls in order to service the evacuation zone.

A common practice in case of a fire is to evacuate the fire floor itself, plus the two floors above and one floor beneath. In the case of unprotected local lobbies, the entire zone (i.e. all the floors between two sky lobbies) should be evacuated, and the local lift group cannot be used due to the absence of a protected lobby.
One important event may have changed the way we need to define our views about zoned evacuation: the attack on the World Trade Centre in 2001. The so-called “9/11 effect” (Barber et al. 2003) has caused people around the world to become less willing to stay in place if instructed to do so. This raises the possibility that a large number of occupants outside the evacuation zone will decide to leave the building “just to be sure”, even in case of “just a small fire”.

7.1.2 Fractional Evacuation

In this evacuation mode, elevators are to be used to evacuate a relatively small, focused group of building occupants. This means that this group can be evacuated quickly while using only a few lifts. As only a limited number of lifts need additional protective measures, this option would be cheaper and easier to implement than total evacuation. It is also possible to use fractional evacuation to relocate the focused group of occupants to an area of refuge. Although the percentage depends on the choice of the building designers and users, experts usually mean somewhere between 2-5% of the building population when referring to the term “fractional evacuation”.

Those who cannot use the stairs because they are mobility impaired due to locomotion issues, excessive weight, cognitive disorders or temporary incapacitation, are a primary consideration for fractional evacuation. Many people only view the archetype “wheelchair users” as the target group, but people with for instance severe asthma or a broken leg belong to this group as well.

Since this evacuation type concerns mainly a small number of occupants with restricted mobility and these people need to remain safe while waiting for rescue, greater protective measures would be required of the lifts and the surrounding lobbies. Therefore a common suggestion is to use fire-fighter’s lifts for the dual purpose of egress for the abovementioned group and ingress of emergency personnel.

7.1.3 Total Evacuation

In a scenario that requires total evacuation, all occupants are completely removed from the structure. Areas of refuge can be useful during the evacuation process, but (eventually) these areas need to be cleared as well.

Scenarios where total evacuation may be considered necessary include catastrophic fires, extreme weather conditions, bomb threats and other (potentially) catastrophic events in the surrounding area.

When a total evacuation scenario occurs, the primary concern is to get all occupants out of the building as quickly as possible while maintaining a safe, orderly procedure: lifts can play an important role to achieve this. The exact method can differ, depending on the chosen method of evacuation (several combinations of stairs and lifts, with an additional team in charge of fractional evacuation), but it is likely that all building elevators will be used to achieve the largest evacuation flow. Therefore, all elevators need to be given due consideration in respect to protected lobbies, hardened lift carriages et cetera.

Note that the fire department may require a number of lifts (two lifts according to current Dutch building codes) to be reserved for sole use by fire-fighters. These lifts, with stops at every floor, can therefore not be used by the Appointed Safety Supervisors (ASS) unless the fire department and the ASS team have an agreement regarding the usage of these lifts.
7.2 Protecting the vital areas and weaknesses of a lift system

Lift systems have many vital components. When understanding the threats to and weaknesses of a lift system, it should be possible to design safety features that reduce these threats to an acceptable level and provide additional protection for the vital areas.

The previous chapter illustrated how lift shafts in a building are potentially huge threats during an incident: the shafts provide an open connection to a large number of floors and thus can spread for instance smoke and hot gasses to other floors, easily bypassing other forms of compartmentalisation. For this reason, a number of the vital components described here have something to do with the separation between the shaft and the rest of the building.

7.2.1 Compartmentalisation: protected lobby

One way to retain the ‘fail-to-safe’ principle of lifts is to add a physical layer of protection. A lift lobby that has been designed to ensure an enclosed smoke free and fire free environment for a predetermined period of time provides this extra layer. The idea of a protected elevator lobby is a widely acknowledged safety measure: the CTBUH even suggests a number of options in their guideline (2004), see figure 7.4.

In case of a fire, the enclosed area remains shielded from smoke and hot gasses: the direct environment of the lifts is safe, allowing the lifts to remain operational. Every floor now has a refuge area, providing evacuees with a safe place to wait.

The “protected elevator” option in particular creates many options for evacuation strategies where evacuees and/or emergency personnel can switch between lifts and stairs; they can look through the protected glass window of the fire door between stairwell and lift lobby to check whether the lifts are safe to use. The stairs also provide for an alternative evacuation route for any evacuees, should the lift system (despite all the protections in place) become inoperable for whatever reason. As building occupants use the lifts daily, they also are aware of the adjoining stairwell(s) next to the lift lobby, making the emergency egress route more familiar. This makes the lift lobbies the central hubs where people meet, gather information via monitors and head down to safety (while still providing enough compartmentation by the fire doors separating the lobby from the stairwell).

For buildings exceeding a height of 50 m, Dutch law already requires the emergency stairwells to have a protected corridor or “smoke sluice” leading to the actual stairwell.
Emergency stairwells and lifts can share the protected lobbies: this saves space, reduces the necessary capacity of pressurization and/or dilution systems and allows for direct access between the two means of emergency egress. As soon as any smoke or hot gasses are detected by sensors inside the protected lobby however, it is assumed that the fire barrier has failed. The lobby isn’t safe anymore, so the lifts in that lobby automatically switch into the emergency recall mode, head down to the bottom level and shut themselves down (note however that elevator landing doors are required to have an additional fire/smoke resistance of 60 minutes, see paragraph 7.2.5).

There are a few complications that arise when trying to retain the ‘fail-to-safe’ principle. Note that the initial (fire) alarm already triggered the first emergency lift recall: in this (second) case where the lobby sensors trigger the warning that a lobby has been breached, these lifts are likely being controlled with a special override key, used by a fireman or member of the ASS team. This means that this lift will *not* head down (for the second time), avoiding the possibility of trapping personnel at the floor where they were operating but also becoming an unacceptable safety hazard for them. This problem could be solved by the triggering of an alarm inside the lift car and outside the landing door (lights and sound), informing the emergency personnel that the safety of that lift (group) has been compromised. Emergency personnel who decide to ignore the warning however may find themselves trapped inside the lift car once the lift systems fail. This dilemma should be addressed by making clear choices and instructing emergency personnel very clearly about what to do when the safety of a protected lobby (and thus the lift group) is compromised.

A second issue is the lobby of the incident floor(s). While the building occupants at the incident level flee from the fire in their area through the lobby and into the adjacent emergency stairwell, some smoke will probably migrate along with them through the open door. Although the sensors inside that particular lobby are crucial to monitor the conditions inside the lobby and trigger a warning if the fire partition has been compromised during a later stage, the emergency recall protocols of the lift system should be able to differentiate the smoke in the initial stage at the incident floor, in order to keep the lifts usable for evacuation.

The most obvious solution to prevent or at least minimise this smoke migration is the pressurisation of the lift lobbies along with the pressurized lift shafts and stairwells. Another option is to use enhanced smoke detectors in the lobby, with for instance infrared sensors in addition to the standard optical sensors.

7.2.2 Pressurisation and dilution systems

High-rise buildings in particular are vulnerable to the stack effect, where the rising warm air (from, for instance, a fire!) effectively turns high vertical shafts into giant chimneys,
fuelling any fire with more oxygen and spreading smoke and hot gasses into the shaft and to other floors.

Pressurization can be used to keep out smoke and hot gasses. Air leakage is a substantial problem however, especially when people keep the doors open while streaming into the emergency stairwells to head down to safety. By pressurizing the protected lobbies between the lift shafts and the emergency stairwell, one integrated system is created: this would likely reduce leakages and pressure differences. If the door leading into the protected lobby is opened, the airflow would help keep any of the smoke that migrated along with evacuees at the incident floor out of the secure area.

The Dutch SBR (2005) states that pressurized emergency stairwells should be segmented when they exceed a height of 50 meters: this measure aims to keep the required volume to be kept under pressure realistic, with the maximum capacities of the pumps in mind. Another, equally important issue is that the pressure differences between two sides should not exceed a maximum value. In case of doors leading to the emergency stairwell, the maximum pressure shouldn’t exceed 90-100 Pascal or a door opening force of 133N (NFPA 2006), so that the average person still is able to open the door despite having to push against the airflow in. SBR (2005) also adds the minimum pressure requirement of 50 Pascal, which is needed to counteract the combined influence of stack effect and possible pressure differences caused by the wind.

In the case of lift shafts, segmentation into sections of 50 meters is obviously not feasible, which means that the air leakage through the landing doors should be kept as little as possible. With lifts, pressure differences exceeding 30-50 Pascal could cause the landing doors to become jammed. Protected lobbies could act as a buffer area and reduce the pressure differences between the lift lobby and the lift shaft. The step-by-step increase of pressurization from workspace, to protected lobby, to the lift shaft and emergency stairwell, reduces the opening forces of fire doors and can prevent additional costs needed for stronger lift door operating motors.

A dilution venting system could be an addition or even an alternative to stairwell pressurization. This system uses the supply and exhaust air to dilute any smoke penetrating the stairwell. The named benefits of this system are a net neutral pressure differential in the stairwell with respect to the floor served, longer continuous stairwell runs in super tall high-rise buildings and limited overpressures due to stack effect. Stack effect pressures could be relieved at the top of the stairwell using barometric relief dampers, without the active protection system adding to the overpressure that would need to be relieved (Ferreira et al. 2008).

Figure 7.6: Fire Dynamics Simulator (FDS) models for 20-storey stairwell with fire compartment adjacent to the 5th floor of the stairs (Ferreira et al. 2008). Left: all doors to the stairwell assumed closed. Right: fire compartment door closed and the doors on other floors partially open.
7.2.3 Emergency power grid

While emergency stairwells can be fitted with fluorescent and/or battery-powered lighting, lift systems and ventilation/pressurization systems need a strong, reliable source of power to remain functional. Most publications therefore advocate the requirement of an emergency backup generator. There are more methods available though to provide the required reliability and redundancy however. The Delftse Poort, the second case study described in chapter 12 of this thesis, has a secondary power grid that ensures a continued closed circuit, should the primary grid become severed for whatever reason. The different lift groups can be divided into separate electrical circuit groups as well: the SBR (2005) requires for instance that the reserve fire-fighters lift should operate completely independently from the primary fire-fighters lift: this means separate lift shafts and separate lobbies, but also separate power grids.

7.2.4 Different lift modes

One possibility to enhance safety would be to design the lift system to have different lift drive modes with priorities depending on the situation at hand (Bärlund et al. 2006). A rule of thumb is that emergency drive modes override standard drive modes. The order of elevator system mode prioritization is proposed in figure 7.7. The situation at hand dictates the mode to be used.

Non-fire (total) evacuation becomes necessary mostly in situations where the building and its systems are under threat, but not yet damaged. Evacuation during a fire requires a different setting, where the building’s fire system (input from smoke/temperature sensors etc.) continually monitors the safety of the lift systems. An extraordinary event like an earthquake or large explosion would trigger the system to revert to a slow drive mode and stop at the nearest landing, avoiding entrapment of the occupants inside.

7.2.5 Lift doors and access points for emergency rescue

Lift doors are one of the moving components of the lift system, which makes them more susceptible to wear and tear. Building occupants are a frequent cause of damage, forcing a closing door back open to squeeze inside at the last moment or accidentally driving a heavy food trolley against a door. Accumulated filth can clog up rails and jam lift doors. When exposed to heat, lift doors may deform, making them an obstruction and widening existing crevices. Even under normal circumstances the crevices between and around lift doors allow for substantial air leakage, facilitating the possibility for the stack effect or the migration of smoke and hot gasses into the lift shaft.

As explained in paragraph 3.4.2, Dutch law requires an access point at least once every 11 metres, which usually corresponds with one access point for every three floors. The reason behind this is to limit the vertical distance that needs to be traversed, in case people stuck inside a lift need to be rescued (the practical height for a ladder shouldn’t exceed 11 meters). Normally the landing doors can be opened by emergency personnel in order to gain access, but mid-rise and high-rise section don’t have landing doors in the zones that they don’t service. Even a region with no landing doors however has “holes”, in the form of maintenance access doors. This means that the idea that lift shafts are impenetrable bunkers, is incorrect.

Proper reinforcement and fire resistance of the lift and access doors should minimize the threat caused by the extra “holes” in the shaft. Note that the desired fire resistance may need to be higher than other doors, depending on their location; lift doors may be...
shielded by a protected lobby, but if the emergency access doors aren’t, they might need extra protection.

As per Dutch law (NEN-EN 81-1) lift shaft doors need to be fire and smoke resistant for at least 60 minutes. Designers are exploring new ways to reduce crevices and increase door strength and reduce deformations (by reinforcing them with honeycomb structures, for instance). Raising the thresholds of the landing doors and sloped floors in the lobbies will prevent water from leaking into the lift shaft (Klote et al. 1993, Proulx 2009).

7.2.6 **Machine rooms**

Usually lift machine rooms are situated above the lift shaft. If the lift drive mechanisms are damaged, the lifts won’t work. The machine rooms are therefore crucial areas that need proper protection. If one of the machines catches fire, the other machines should be able to keep functioning after becoming wet by the sprinkler system. The necessary ventilation needs to be continued (via a separate, secondary system), and the ventilated air should preferably remain clean and free of soot.

A number of improvements are possible for machine rooms. Compartmentalisation is an example: one could even decide to add compartments between machinery of different lift groups. Instead of (or in addition to) hardened machinery, one could choose to shut down a lift group in one compartment and still be able to use other groups for evacuation. Other improvements include provisions to minimise the leakage of sprinkler water into the shaft below.

7.2.7 **Lift alignment system, lift sensors and electrical systems**

A lift system is comprised of a number of subsystems, many of these quite sensitive and easily disrupted. A number of sensors are situated above and below every landing, relaying the position of the lift car in respect to the landing. The lift system uses these references to slow the car down and align it vertically to match the landing floor. This system is susceptible to malfunction and short-circuits, whether due to smoke, soot, water, airflow or obstructions.

By “hardening” a lift, these systems are less vulnerable to outside influences (water, smoke) and remain operable for a longer period of time despite these influences. The goal is to maintain lift operability, even under adverse conditions. In this process it is extremely important to define the difference between adverse conditions and dangerous conditions in the decision whether the lift system still is safe enough for use.

7.2.8 **Horizontal compartmentation**

In particularly high buildings, lift groups are stacked upon each other: a building divided into sections with sky lobbies is a well-known example of stacked lift groups. In order to limit cable lengths, local lift groups have their own machine rooms: this means that the lift shafts of these stacked lift groups are separated by the lift machine rooms.

Horizontal compartmentation between the different floors of a building is already a requirement and is crucial to prevent fire/smoke spread to floors above and below the incident level. Further compartmentation, for instance of zones, can ensure independent operability of these zones. If the systems of one building zone fail (for instance due to a fire at the level for mechanical systems), the other building zones remain operable, thus reducing the area of effect of this failure.
7.3 Using building zones and horizontal compartmentation

7.3.1 The concept of rendezvous floors

The idea of grouping building occupants at rendezvous levels or "transition floors" has already been devised in the 70's (Pauls 1977, 2005). Lifts are grouped in a low-rise, mid-rise and high-rise section, depending on the building (section) height. This layout can also serve as the layout of the rendezvous levels. Figure 7.8 illustrates an example building, with two lift groups servicing a high-rise and a low-rise zone. All lifts of the high-rise section assemble at the upper rendezvous level; from there they shuttle the people arriving at that rendezvous level down to the ground floor. The low-rise elevators service the mid-rise section, and the people of the low-rise section head directly down to ground level.

Commercial buildings will typically use Appointed Safety Supervisors: the chief coordinator sends teams to the rendezvous levels, where they can guide the transition of the traffic by stairs into the lifts in an orderly fashion and prevent problems caused by crowding, overloading ands forth. Less rendezvous levels keeps the process simple and easy to manage: it means less teams needed to coordinate the evacuation procedure, and thus a better overview and less communication nodes (i.e. less clutter over intercoms and/or portable radios).

7.3.2 Using segmentation

Note that segmentation of the emergency staircases can greatly simplify the path of egress to these rendezvous points: the segmentation simply forces you to leave the staircase at the correct height and enter the protected lobby of the rendezvous level, where an ASS team receives you. After waiting your turn, checking the monitors for more information and talking with your fellow colleagues, you are grouped and assigned to one of the lifts shuttling up and down. If necessary, one could enter the new segment of the stairwell and continue downward.

Combining the segmentation of the staircases to match the transfer floors between lift groups in a building allows for "logical" division of the building when assigning lift groups to service the rendezvous levels during an emergency egress situation. The low-rise lifts can be used to shuttle the occupants of the zone above it, for instance. A transfer floor is a term used in the lift industry, where a building occupant can switch between lift zones (for instance from low-rise to mid-rise), see section 3.4.1.

7.3.3 Using local lifts as backup for shuttle lifts

It is possible that the shuttle elevators servicing a sky lobby aren’t operable. The shafts of shuttle elevators are relatively high and cannot be compartmented; they can also be simply out of order at the time of the incident. While extremely unfortunate, this remains a possibility. In this case, the building occupants who arrive at the skylobby are redirected back down the stairs to, for instance, one floor below the skylobby.

The results in chapter 11 show that local lifts typically take 10-12 minutes to empty the local zone. They also show that the shuttle lifts typically take 40-50 minutes. Once the local lifts of the zone below have cleared ‘their’ population, they can be used to help evacuate the people waiting in the skylobby above or even replace any defunct shuttle lifts.
7.4 Organisation, information and communication

The importance of the quality of the combination of organisation and information has already been stressed in section 5.3. In building safety engineering, “less is more” and “keep it simple” are key phrases for a successful emergency egress system. When using lifts in the evacuation process, the importance of a well-organised and well-executed evacuation may be even higher, due to the implementation of a second egress method and thus the addition of another cog in the wheel.

7.4.1 Building officials, local authorities and emergency services

As the Dutch national building codes do not cover buildings higher than 70 meters, a (future) building owner needs to confirm with the local authorities whether the building is safe for use. The city council and the local fire department are also obligated to ensure the building’s continued safety by means of regular inspections. Consent from these parties is therefore crucial when implementing all building safety features, and because the use of lifts for evacuation is rare in the Netherlands, getting that consent will require an excellent presentation of an excellent evacuation strategy.

The prerequisites that need to be addressed include:
- A clear, straightforward evacuation protocol that is easy to understand.
- A report arguing how and why the combined safety systems are reliable enough to implement the proposed evacuation strategy. It should include the answers to questions like: “What is the chance of failure?”
- For the question “What will you do, just in case this system fails?”, a contingency plan without lifts can be provided.
- Show the added value of the lifts by comparing egress times etc. with the ‘traditional’ method.

The organisational structure in particular should be addressed:
- The structure of the building's ASS team, building security and building management.
- The structure and standard operating procedures of the local fire department.
- The timetable of the activities between detection and arrival of the fire department.
- The building’s contact person and location of the meeting point.
- The location and functions of the Fire Command Station. The SBR document (2005) specifically addresses the FCS, its location and required functions.
- How the duties and responsibilities shift upon arrival of the fire department: who is in charge of what?
- The continuing timetable after the fire department’s arrival.

Regular, joint drills with the fire department will serve to attune the Standard Operating Procedures (SOPs) of the ASS team and the emergency response personnel, if the drills are properly evaluated and if improvements are made based on their conclusions.

7.4.2 The evacuation procedure

The evacuation procedure itself should be clear for the building occupants, the ASS team and the emergency responders: people need to know what to do, where to go and when, what their tasks are and what they are not.

- What is the standard evacuation procedure? Are there different procedures, depending on the nature of the incident? How do we know what procedure to follow?
- How are the Appointed Safety Supervisors and the building occupants warned?
- What are the initial procedures of ASS personnel: where do they go to form teams, who is in charge on that floor, where can they receive more information, how and from who?
- How much information do building occupants receive and in what way (spoken text, monitors, locking computer networks to send instructions etc.)? Where is what information provided (for instance more elaborate info in secure lobbies)?
- Where should the occupants assemble (multiple egress points?), how does the ASS team achieve this and when are people allowed to enter the stairwells / evacuation lift?
- Who is in charge of the evacuation lift(s), who operates them and what floors are to be evacuated via lifts? In case of multiple floors, in what order?
- Which building occupants are allowed to make use of the evacuation lifts? Where should they assemble and how do they know this?
- What is the role of ASS personnel once the emergency services arrive? How are they informed about their shift in duties and responsibilities?
- What to do if no information is available?

Again, proper training and regular fire drills should serve to make the building officials, ASS personnel and building occupants knowledgeable about what would happen in an emergency and what they are expected to do. Proper evaluation will provide the option to locate and solve communication problems, confusion due to flawed routing of egress paths et cetera.

7.4.3 Appointed Safety Supervisors
Nearly all non-residential buildings in the Netherlands have ASS teams, consisting of employees that volunteer to be a part of these teams and agree to the additional training, drills and evaluations that are required besides their regular duties. Larger companies usually have separate employees, dedicated to the organisation and management of the security and/or safety systems, who oversee the drills and act as a spokesperson/contact for the emergency services.

One important question is the required level of responsibility required from ASS personnel at the different levels. The quality of the leadership skills of the fire wardens on all floors varies greatly per company, and even with proper training their reliability may vary when confronted with an actual emergency. Floor wardens are volunteers after all, with probably little to no real-life experience. It is therefore crucial to ensure that the key locations are staffed in order to protect the important procedures, for instance by having dedicated teams who assemble at a central location. After confirming that enough staff have been appointed for all key locations, they can proceed with the important tasks like manning rendezvous floors and operating the evacuation lifts.

7.4.4 Buildings without Appointed Safety Supervisors
Residential buildings generally do not have personnel that can double as Appointed Safety Supervisors, which means that information, communication and particularly organisation is more difficult. This is the reason why this thesis advocates leaving the use of lifts for evacuation entirely in the hands of the fire department. Another reason is that fire drills are held rarely in residential high-rises, if at all, making training almost impossible.

7.4.5 Reliability and maintenance of active systems
The misconception that passive measures like compartmentation are by definition more reliable than active systems, has been addressed in chapter 5. When regarding lift systems, one could argue that also in this case this active system is more reliable than passive fire protection, because any malfunctions in the lift system will be noticed and tended to during normal operation.

One important part of the organisational aspects of the building safety system is the scheduling of maintenance and repair activities. The building management team could limit the amount of lifts that are temporarily inoperable during maintenance work or decide to schedule these activities outside the regular hours of the workday. During a
workshop hosted by the Dutch NEN in February 2010, regarding the use of lifts for evacuation purposes in high-rise buildings, the assembled experts from various fields of expertise agreed that, for calculation purposes, one lift should be considered out of order. Opinions varied whether the calculations could include the reserve fire-fighter’s lift as a substitute for the inoperable lift.

7.4.6 Deciding the evacuation strategy

One of the crucial stages during the emergency procedure is the decision regarding the further course of actions. Building officials have created a number of SOPs based on the nature of the emergency: for example zoned evacuation coupled with the defend-in-place strategy for a contained fire scenario, total evacuation using lifts in case of a bomb threat and total evacuation using only stairs in case of a severe earthquake.

The different evacuation strategies require different evacuation mode settings from the lift systems and different SOPs for the ASS teams and emergency personnel. This requires one moment in time where the person responsible for security makes the decision that defines the protocol to be followed from that moment on. In buildings with professional security personnel present, this decision can be made by the person who has been assigned this responsibility; in buildings without any authority figures present (like most residential buildings), this decision can only be made once the emergency services have arrived and established the necessary chain of command. Siikonen et al. (2005) illustrated the impact of this decision in figure 7.9:

The flow chart shown above is comparable to the diagram in section 5.4.1. In addition, this diagram emphasises the phase the lifts stop functioning in normal service, the period of time when the lifts have been recalled and await the decision regarding the evacuation protocol to be used, then followed by a number of possible evacuation modes. Note that the three evacuation modes depicted in the diagram belong to the evacuation strategies described in the publication by Siikonen et al., which have a different setup than the strategies described in this thesis. The general concept however remains the same: the evacuation of a building needs to be managed step by step, with clear, unambiguous protocols.
8 A MATRIX OF EVACUATION TYPES AND SCENARIOS

In this chapter all possible evacuation types will be explored, in varying steps from "only stairs" to "only elevators" and from staged to total evacuation. In section 8.2 a number of scenario's will be described for which evacuation is necessary in some form or other. In 8.3 the possible evacuation types will be considered for each scenario and the pros and cons of each possible solution will be examined. In addition the distinction will be made between residential and commercial buildings (8.4). This will result in a matrix in which for each scenario the most efficient evacuation type(s) are listed.

8.1 Evacuation types

The CTBUH considers three main evacuation types (CTBUH, 2004): total evacuation, phased evacuation and fractional evacuation. These three can be divided into different subtypes and combinations. The choice of using lifts, stairs or both, adds to the amount of possibilities.

An important note beforehand: the listed possibilities describe buildings without a sky lobby-shuttle lift system or a section of the building between two sky lobbies: the “rescue area” can therefore either be the ground floor / main exit level or a sky lobby. Sky lobbies are considered to be compartmentalised as refuge areas: it is also assumed that the shuttle lifts servicing the sky lobbies are functioning normally and are used to transport the occupants of that building section further down to the main exit level.

8.1.1 Total evacuation – stairs only

This can also be termed as the “null solution” or the current situation: “In case of fire, do not use the lift!”

This evacuation type has been added to provide comparison between evacuation times using the current procedures, and the evacuation times of the proposed methods.

8.1.2 Total evacuation – lifts only

This evacuation mode assumes that the entire building population is evacuated using lifts only. This is the exact opposite of the “stairs only” null solution, and may be just a theoretical solution as well.

The reason why this option is probably not the optimal solution, is that legislative parties (and plain common sense) will simply not allow the removal of all emergency staircases from the building (safety) design: it would not be wise to put all one’s faith in lifts for evacuation and not provide at least two emergency stairwells, just in case.

Having established this, it would be a waste of resources not to use these stairwells in conjunction with lifts: after all, the potential handling capacity of the stairwells would remain unused. However, the possibility remains that this option may prove to be surprisingly efficient.

8.1.3 Fractional evacuation – fire department only (constant fractional evacuation)

The most “conservative” solution after the null solution is fractional evacuation, using only fire-fighter lifts. The majority of the building occupants still use the stairs for emergency egress, and only a fraction of the people use the (fire) lifts, under supervision of the fire department. An important note is that for this reason, fractional evacuation while using fire-fighter lifts can only commence after the fire department has arrived and is ready to start with the search & rescue procedure (otherwise known as the intervention time, see section 5.4).
As explained in section 7.1.2, fractional evacuation only targets a relatively small part of the total building occupation, specifically the (temporarily) disabled and other high-risk groups. In this particular evacuation type the choice has been made to follow the following procedure: the people belonging to the high-risk group are instructed to head towards the protected lobby that contains the fire-fighter’s lift. There they need to wait for the fire department to arrive and a team to collect them, using the fire-fighter’s lift.

In case of fractional evacuation, the designated lift needs to be able to stop at each floor: the fire-fighter’s lift satisfies this demand. In case of constant fractional evacuation, the model assumes a fixed percentage of every floor being evacuated by lift.

Fractional evacuation can be used alongside other evacuation types to alleviate the traffic flows of the ‘normal’ evacuees and reduce congestion. It can therefore increase the stairway handling capacity to such an extent that no additional measures are needed to get everybody out in time.

8.1.4 Fractional evacuation – in-house appointed safety team (constant fractional evacuation)

Instead of using fire-fighter lifts and therefore being forced to wait for the fire department, fractional evacuation could be attained using ‘normal’ lifts and specially appointed safety teams.

The fractional evacuation process can be guided by a team of appointed safety supervisors, who collect the people that need this ‘special’ evacuation, following the procedure that has been decided upon (see section 7.1.2). The advantage of this option is that the evacuation process can commence without needing to wait for the fire department to arrive on site.

In case of fractional evacuation, the designated lift needs to be able to stop at each floor, or the safety team will need to switch lifts when switching to the high-rise, medium-rise or low-rise section. The fire-fighter lift should remain available at all times for the fire department, unless specific agreements have been made that the appointed safety supervisors are allowed to operate the fire-fighter lift during the time it takes for the fire department to arrive.

In case of constant fractional evacuation, the model assumes a fixed percentage of every floor being evacuated by lift: in other words, we assume that the percentage of occupants using the lift for emergency egress is (roughly) the same for every floor.

8.1.5 Total evacuation – stairs – transfer floors – lifts in shuttle mode

In this evacuation mode, the lifts of the local lift groups are divided into a few groups and are directed to a designated rendezvous level. When the evacuation alarm is triggered, the building occupants are instructed to head down to the nearest rendezvous level using the stairs. Once there, they continue the journey down to the rescue area via the lifts, which are now in shuttle mode and no longer respond to hall calls.

As has been explained in section 7.3, transfer floors and segmented stairwells allow for clear guidance towards the rendezvous level. Therefore it is assumed in this evacuation mode that the transfer floors are the rendezvous areas, and that stair segmentation has been designed to match the transfer floors. Transfer floors are floors where the landings of different lift groups (for instance low-rise and high-rise)
overlap, giving building occupants the option to switch between lift groups at that level. This means that relatively large amounts of people make use of these levels and therefore are familiar with them.

Alternatively, emergency transfer floors can be created by adding extra landing doors in the lift shafts of the high-rise lift group, at the highest floor of the low-rise zone.

8.1.6 **Total evacuation – stairs – transfer floors + half levels – lifts in shuttle mode**

This evacuation type is basically the same as (8.1.4), with the following addition: instead of only assigning transfer floors as rendezvous areas, an extra rendezvous floor is assigned between the two transfer floors. These rendezvous floors will be referred to as transition floors: a transfer floor is therefore also a transition floor, but a transition floor isn’t necessarily a transfer floor.

The reasoning behind this option is that the number of floors between two transfer floors can exceed 20 floors (≈70 meters): this option halves the number of floors that need to be traversed by stairs. This may prove useful if the average person slows down significantly after, for instance, 10 floors (≈35 meters).

Note that, for this evacuation type, stair segments can be halved as well to match the extra rendezvous areas.

8.1.7 **Total evacuation – stairs and lifts, free choice (proportional fractional evacuation)**

This evacuation type assumes that each floor will be served by lifts during emergency evacuation: the choice between using the lift or the stairs is left up to the building occupants.

Proportional fractional evacuation is basically an effort to incorporate free will of individuals into the model. It assumes that the number (or “proportion”) of the building occupants who are prepared to wait for a lift to arrive, increases with the height of their floor. For example: at the third floor of a building, only those with mobility impairments will need the lift to get to the ground level. On floor #20 though, people are used to taking the lift in normal situations, are used to relatively long waiting times and are prepared to wait for the lift during an emergency situation as well (knowing the amount of stairs they would otherwise have to traverse).
The evacuation time depends on the way the lifts service the floors (bottom-up, top-down etc.). This method is difficult to predict, as the proportion of people travelling by lift versus stairs can vary in many different ways, see section 10.3.2. This method is arguably the most chaotic one, and without proper information via monitors, for instance, there is a high risk of deviations from the model.

Will the occupants of every floor be equally prepared to follow the given directions, or will they follow their own plan? This question is difficult to answer, and further research is necessary. By means of simulation software, patterns may be found describing the choice of evacuees to use the stairs or the lifts as a function of the height of a building. Once this pattern has been found, it may be able to incorporate this pattern into design calculations.

8.1.8 Total evacuation – stairs and lifts, free choice affected by incident level

This option is a special example of proportional fractional evacuation. This model assumes that the location of the incident influences the behaviour of the building occupants, and therefore the choice of those people to take the stairs or the lift.

For instance: a fire has developed at the tenth floor. The occupants of that floor will probably all take the stairs, wanting to get away from the danger as soon as possible. As the developing fire starts to cause smoke to rise from the windows and up along the building, it is reasonable to assume that when the people in the floors above floor 10 see the smoke, the sense of urgency will be more present and a relatively large amount of people will want to use the stairs instead of waiting for the lifts. At floor #30 however, where the wind has blown away any traces of smoke, its influence is probably negligible.

One could conclude that the influence of the incident level depends on the measure of the incident’s “visibility” in respect to the building occupants. Also, behaviour like the “9/11 effect” can influence this model.

8.1.9 Zoned evacuation

In the case of zoned evacuation, only the floors in the vicinity of the incident level are cleared. The evacuation of these floors can be done using stairs, lifts, or both. Zoned evacuation via stairs isn’t likely to cause congestion, due to the limited amount of building occupants being evacuated. The stair handling capacity has been calculated for a total evacuation scenario, so the measures designed for total evacuation (as described in 8.1.1 through 8.1.8) can easily be used for zoned evacuation.

Zoned evacuation will therefore not be included in the calculation matrix.

The safety provided by the (horizontal) compartmentalisation of sky lobbies enables the strategy that all lifts in the building sections below the section with the incident level stay functional. This coincides with the ‘defend-in-place’ principle, where only the area of the incident level requires evacuation.

The question whether different rules should apply for these levels (“Do not wait in the protected lobby, but evacuate everybody in this zone ASAP via the stairs”), or the question whether it is feasible to allow other building zones (and thus the other local lift groups and shuttle lifts, where applicable) to continue functioning normally, are important issues that need to be addressed.

Note that, no matter which strategy is used, the current practice is to evacuate the incident level ASAP, plus 2 levels above and one below.
8.2 Scenario's

One of the main factors that decide which evacuation model is most suitable is the scenario that causes the need for evacuation in the first place. An earthquake will require more extensive measures than a dustbin fire, for instance.

8.2.1 Local incident

A local incident is a dangerous incident that happened (or is happening) inside the building. Additionally, the incident occurred or originated in a relatively small compartment of the building.

A fire is an example of a localized incident.

8.2.2 Global incident

A global incident involves the entire building and usually is caused by an external event.

A blackout causing the entire building to lose electrical power is an example of a global incident. Earthquakes, tsunamis and toxic gas clouds (caused by for instance a fire near the building) are other examples.

Global incidents like earthquakes have the added risk that the reliability of the lift system may be compromised. Even if the structural integrity of the building has been preserved, the tremors may have triggered shunt breakers of the lift system, or the alignment of lift guide rails may have been affected. This is an important possibility to take into account when integrating lifts into evacuation design: what is the probability that the lift system is offline and which parties are qualified to judge whether the continued usage of lifts is safe or not (see section 7.2)?

8.2.3 Global threat

A global threat encompasses situations where nothing has happened yet, but that there is a potential threat of a dangerous situation, affecting the entire building.

Bomb threats and hurricane warnings are examples of global threats.

8.3 Building types

Another main factor influencing the suitability of evacuation types is the building type. The three building types described below cover the primary functions of most high-rise buildings.

8.3.1 Office buildings

Office buildings function as areas where people come to work during the day: when finished for the day, these people leave the building. An office building may have additional social functions or facilities like restaurants, but they explicitly do not have the function of staying overnight. This means that the average reaction time of building occupants is relatively quick, making options where evacuation can start before the fire department arrives more effective. Companies usually use the system of appointed safety supervisors, who act as the initial response team until the fire department arrives to take over.

In this thesis the following assumptions have been made in regard to office buildings:

- Office buildings have appointed safety supervisors.
- The average reaction time of the building occupants is short.
8.3.2 Residential buildings

The purpose of a residential building (rest & relaxation, sleep) affects the reaction times: the occupants of residential buildings usually have more trouble reacting swiftly (getting dressed in the night, the desire to save the family photos etc.). This means that the fire department’s response time isn’t that long compared to the reaction time. The building occupants of a residential building have a different composition in demographic aspect (elderly people, children), and group behaviour (families stick together) may be quite different. These buildings also often lack the system of appointed safety supervisors that office buildings usually have.

The following assumptions have been made in regard to residential buildings:
- Residential buildings do not have appointed safety supervisors.
- The fire department is the only party capable of supervising the evacuation process.
- The average reaction time of building occupants is relatively long.

8.3.3 Hotels (Dutch: logiesgebouwen)

A hotel functions as an area of recreation, including overnight stay. This makes reaction times in hotels relatively long, but probably shorter than in residential buildings (short-term residence, no emotional attachments etc.). The building population is quite diverse, like in residential buildings. The hotel staff can act as appointed safety supervisors: in fact, their involvement as employees arguably makes them an even more effective team, with better knowledge of the entire building.

The following assumptions have been made in regard to hotels:
- Hotels do have appointed safety supervisors.
- The average reaction time of building occupants is relatively long.

8.4 The decision matrices

Some evacuation types are better suited than others, depending on the scenario and building type. This paragraph shows in three matrices, which options are feasible or not, given a certain scenario and building type. Note that these matrices do not yet encompass the preferred method(s) of evacuation. The scale does include the differentiation of options that are (technically) feasible, but difficult to actually realise, for reasons that will be explained in the following paragraphs.

The options are rated according to the following scale:
- Not feasible or not applicable;
- Feasible, but undesirable or difficult to implement;
+ Feasible.

8.4.1 Matrix #1: office buildings

This matrix shows the possible evacuation strategies for office buildings:

<table>
<thead>
<tr>
<th></th>
<th>Local incident</th>
<th>Global incident</th>
<th>Global threat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Total evacuation – stairs only</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2) Total evacuation – lifts only</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>3a) Fractional evacuation – fire department only</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>3b) Fractional evacuation – in-house appointed safety team</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>4a) Total evacuation – stairs – transfer floors, lifts in shuttle mode</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>4b) Total evacuation – stairs – transfer floors + half levels, lifts in shuttle mode</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>5a) Total evacuation – stairs and lifts, free choice</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5b) Total evacuation – stairs and lifts, free choice affected by incident level</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6) Zoned evacuation</td>
<td>+</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 8.1: Matrix #1: office buildings
Without the function of staying overnight, the average reaction time is relatively quick in office buildings. This makes options where evacuation can start before the fire department arrives more effective. The use of appointed supervisors is possible: this makes the more controlled evacuation strategies (like 4a and 4b) more feasible. As office buildings are relatively densely populated and that occupants of office buildings are relatively quick to react to an evacuation alarm, the traffic flows are relatively dense: many occupants make use of the egress infrastructure in a relatively short time period. This causes the evacuation procedure to need a high level of control, making the ‘free choice’ options (5a and 5b) most probably undesirable. Note that, in the case of a global incident, the increased risk has been taken into account that the lift system may not be reliable. This makes it strongly advisable to suspend lift usage until trained emergency response personnel have arrived.

8.4.2 Matrix #2: residential buildings

This matrix shows the possible evacuation strategies for residential buildings:

<table>
<thead>
<tr>
<th></th>
<th>Local incident</th>
<th>Global incident</th>
<th>Global threat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Total evacuation – stairs only</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2) Total evacuation – lifts only</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>3a) Fractional evacuation – fire department only</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>3b) Fractional evacuation – in-house appointed safety team</td>
<td>x</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>4a) Total evacuation – stairs – transfer floors, lifts in shuttle mode</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4b) Total evacuation – stairs – transfer floors + half levels, lifts in shuttle mode</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5a) Total evacuation – stairs and lifts, free choice</td>
<td>+</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>5b) Total evacuation – stairs and lifts, free choice affected by incident level</td>
<td>+</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>6) Zoned evacuation</td>
<td>+</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Table 8.2: Matrix #2: residential buildings

The occupants of residential buildings usually have more trouble reacting swiftly (getting dressed in the night, the desire to save the family photos etc.), which results in a longer reaction time. This means that the fire department’s response time isn’t that long compared to the reaction time. The building population also consists of a relatively wide range of people (elderly people, children) and group behaviour (families stick together) may be quite different. Due to the variation of reaction times of the occupants, the egress traffic flows are spread out over a longer period of time. There are no appointed supervisors to help with the evacuation process; this means that the more elaborate egress procedures (like 4a and 4b) are difficult to implement and that the notion to “keep it simple” is the governing factor.

8.4.3 Matrix #3: hotels / restaurants

This matrix shows the possible evacuation strategies for hotels:

<table>
<thead>
<tr>
<th></th>
<th>Local incident</th>
<th>Global incident</th>
<th>Global threat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Total evacuation – stairs only</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2) Total evacuation – lifts only</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>3a) Fractional evacuation – fire department only</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>3b) Fractional evacuation – in-house appointed safety team</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4a) Total evacuation – stairs – transfer floors, lifts in shuttle mode</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>4b) Total evacuation – stairs – transfer floors + half levels, lifts in shuttle mode</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>5a) Total evacuation – stairs and lifts, free choice</td>
<td>+</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>5b) Total evacuation – stairs and lifts, free choice affected by incident level</td>
<td>+</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>6) Zoned evacuation</td>
<td>+</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Table 8.3: Matrix #3: hotels

Reaction times in hotels are relatively long, but probably shorter than in residential buildings; the building population is relatively thinly populated, diverse and group behaviour is a possible issue. This makes evacuation with free choice (5a and 5b) a possibility, although a more controlled evacuation (like option 3 and 4) may be preferable. The hotel staff can act as appointed safety supervisors, creating the
possibility of controlled evacuation: given the relatively long reaction times however, it is questionable if the use of an ASS team would be able to evacuate many people before the fire department arrives. Once it does, the ASS team would have to make way for the emergency personnel, cutting the time period during which they are “useful” short (when considering fractional evacuation, i.e. option 3b, but also with options 4a and 4b).
9 RESEARCH: TRAFFIC FLOW CAPACITY – PEDESTRIAN TRAFFIC

This chapter focuses primarily on the pedestrian egress models that will be used for the egress calculations. The existing models for corridor and stair handling capacities described in section 9.1 will be critically reviewed in 9.2. A suggestion for an improved model incorporating human factors like fatigue will be presented in 9.3.

The calculation results in chapter 11 should show in more detail how one’s choice of evacuation procedure affects the efficiency. The results will also determine if a more detailed pedestrian model provides more insight about the limitations of evacuation by stairs and if the traditional models are sufficient.

9.1 Existing pedestrian models

The benchmark for just about every model for pedestrian traffic is based on John J. Fruin’s “Pedestrian Planning and Design”, written in 1971 (reprinted by Elevator World in 1987). Even though his work is over thirty years old, his terminology, models and even the parameters he used are still being applied today. Another main authority on this subject, Gina C. Barney, based her models for a large part on Fruin’s work. This paragraph will describe these models, which are essential when calculating the necessary time to evacuate an area. Special attention will be given to the parameters used by Fruin/Barney and those used by the Dutch research foundation SBR (“Stichting Bouw Research”), which are slightly different.

9.1.1 Corridor and stairway (handling) capacities

From Barney (2003) we can derive two important equations that describe the capacity of traffic flows within a building: the corridor and the stair (handling) capacities. A third important factor, the portal handling capacity, is defined as either a value depending on its effective width or a typical handling capacity, determined for that particular door type (see also paragraph 9.1.4).

The capacity for a straight corridor can be given as:

\[
C_{c} = 60 \times v \times D \times W_{e} \quad \text{[persons/minute]}
\]

where:
- \(C_{c}\) = the corridor handling capacity [persons/minute]
- \(v\) = the average pedestrian speed [m/s]
- \(D\) = the average pedestrian density [persons/m\(^2\)]
- \(W_{e}\) = the effective corridor width [m]

Stairways require pedestrians in a more conscious, disciplined way. The decrease in speed has been empirically determined at around 83% of the capacity of a corridor (Barney 2003). This gives:

\[
C_{s} = 0.83 \times (60 \times v \times D \times W_{e})
\]

where:
- \(C_{s}\) = the stairway handling capacity [persons/minute]

9.1.2 Full Flow versus Free Flow

The abovementioned pedestrian speed \(v\) and density \(D\) are not independent of each other. Fruin takes into account the fact that people in a crowded area (‘Full Flow’) aren’t able to move as freely as when they have a large amount of personal space (‘Free Flow’). The average capacity and speed in a stairway in a Free Flow and Full Flow situation have been empirically determined, resulting in (possibly) different values for these parameters.
The Dutch SBR uses other values for these parameters, which they have based on conducted studies in the Netherlands (SBR, 2005). A comparison has been depicted in table 9.1. It is important to keep in mind that the values that the SBR uses are specifically based on evacuation studies and that the parameters used by Barney are for general purposes. It is interesting to see however that the values vary only slightly in most cases.

<table>
<thead>
<tr>
<th></th>
<th>Free flow design</th>
<th>Full flow design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barney: corridor</td>
<td>1,5</td>
<td>0,3</td>
</tr>
<tr>
<td>SBR: corridor, Wₑ = 1,0 m</td>
<td>1,6</td>
<td></td>
</tr>
<tr>
<td>Barney: stairs, Wₑ = 1,0 m</td>
<td>0,83</td>
<td>0,6</td>
</tr>
<tr>
<td>SBR: stairs, Wₑ = 1,0 m</td>
<td>0,8</td>
<td></td>
</tr>
<tr>
<td>SBR: stairs, Wₑ = 0,8 m</td>
<td>0,8</td>
<td></td>
</tr>
<tr>
<td>SBR: stairs, Wₑ = 1,0 m (max. density)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 9.1: Average pedestrian flows

The abovementioned values have been derived from Barney’s *Elevator Traffic Handbook* from 2003 and SBR’s *Fire Safety in Tall Buildings*, a Dutch national guideline written in 2005 (see also paragraph 4.1.2). The following additional remarks can be made:

**Relation pedestrian density D and stairway handling capacity:**
- The SBR states that if the pedestrian density remains between (1,6 < D < 4,0), the stairway handling capacity reaches an optimum and remains constant at 1,28 persons/meter/second.
- For a “maximum density” D = 4,0 people/m², the SBR assumes the following pedestrian travel speed: 0,37 m/s in corridors, 0,32 m/s in stairwells. The handling capacity remains the same: 1,28 persons/meter/second.
- Barney states that (in a corridor!) Free Flow design is applicable for densities up to (D<0,3 P/m²), and that the average walking speed decreases linearly for (0,5 < D < 3,0). She also states that the corridor handling capacity reaches an optimum at density of around (D=1,4 P/m²). For stairs, Full Flow occurs at (D=2,0 P/m²).
- For a corridor, Barney calculates: $Cₜ = v * D * Wₑ$ persons/s
- For a stairway, Barney calculates:
  \[ Cₛ = 0.83 * (v * D * Wₑ) = 0.83 * (0.6 * 2, 0 * 1, 0) = 1,0 \text{ persons/meter/second}. \]

Note that the SBR assume slightly higher stairwell handling capacities and higher population densities than Barney does. The higher densities used by the SBR are can be justified by considering that where Barney assumes regular conditions, the SBR calculations have been conducted specifically for evacuation purposes.

**General assumptions:**
- In the table above the density D for the SBR calculation has been assumed to be the same as the density used by Barney, i.e. 2,0 persons/m².
- In a Free Flow situation, the SBR disregards the pedestrian density and bases evacuation time solely on the pedestrian walking speed.

**Pedestrian walking speeds:**
- The assumed walking speeds in stairwells used here are for Barney the typical speed of a commuter: this is 0,83 m/s for Free flow and 0,6 m/s for Full Flow.
- SBR also uses $v = 0,8$ m/s for Free Flow. For Full flow, the derived pedestrian speeds are:
It can be concluded that for Full Flow design the pedestrian speed in the stairway is roughly the same for both the calculations made by Barney and by the SBR. A notable exception is the SBR case of the maximum density: here the pedestrian speeds used by the SBR drop to 0.32 m/s in the stairwell at a density $D = 4.0$ persons/m² (at the landings) and 1 person per two steps on the stair itself.

### Influence of the effective corridor width

- **Barney** uses an effective corridor width of 1.0m in her examples; the SBR uses an effective corridor width of 0.8m. In order to make a decent comparison between both calculation parameters, the SBR value for the speed $v$ has been calculated for an effective corridor width of 1.0m.
- The decrease in corridor width in the SBR calculation would be compensated by either an increased pedestrian speed (which is inadvisable) or by an increase of the pedestrian density $D$. If we assume the speed remains 0.64 m/s, then the new density would become:

$$D = \frac{C_s}{v \cdot W_e} = \frac{1.28}{0.64 \cdot 0.8} = 2.5 \text{ persons/m}^2$$

D = 2.5 still meets the requirement ($1.6 < D < 4.0$), which means that 1.28 can still be used for the stairway handling capacity $C_s$.

Again, it is important to keep in mind that the values that the SBR uses are specifically based on evacuation studies and that the parameters used by Barney are for general purposes. With this fact in mind, the higher values found by the SBR for the stairway handling capacity can be justified.

### Obstructions and effective width

The effective width $W_e$ of a corridor or stairway can be influenced by a number of factors. The effective width is calculated by subtracting the factor caused by an obstruction from the total width.

The factors used by Barney and the SBR can differ in this respect. The reduction caused by a rough wall is 0.2m in Barney’s work, while the SBR uses a reduction of 0.3m for a stairwell. A number of reduction factors are given in table 9.2.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>rough wall</td>
<td>0.2 m</td>
<td>0.15 m</td>
</tr>
<tr>
<td>wall-mounted radiator</td>
<td>0.2 – 0.4 m</td>
<td>~</td>
</tr>
<tr>
<td>small fire appliance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>stairwell, railing (both sides)</td>
<td></td>
<td>0.3 m</td>
</tr>
<tr>
<td>orderly queue</td>
<td>0.6 m</td>
<td>~</td>
</tr>
<tr>
<td>un-ordered single queue</td>
<td>1.2 – 1.5 m</td>
<td>~</td>
</tr>
</tbody>
</table>

Table 9.2: reduction of the effective width due to obstructions

### Portals

Portals are defined as an obstruction, reducing the effective width of a corridor. A portal like, for instance, a fire door, can be the bottleneck that decides the entire pedestrian flow during an evacuation. Fire doors are heavy, are equipped with door-closers and therefore need to be taken into consideration when calculating the total evacuation time of a building.

Special consideration must be given in respect to (extreme) bulk queuing (Dutch: “boogvorming”): this phenomenon occurs when a large group of people is attempting to rush through a narrow portal or other bottleneck, causing a ‘plug’ to form in front of that...
portal in which pedestrian speeds drop to zero. A comparison can be made with ancient roman bridges, where arcs support themselves by distributing vertical pressure forces horizontally towards the sides. Wider doorways reduce bulk queuing, but increase the risk of falling. Table 9.3 shows the results of studies conducted by Peschl (1971) and Stapelfeldt (1976), which both produced very similar results (SBR 1984). Note that the increased capacities shown in this table are negated when bulk queuing occurs or if somebody falls down, causing the capacity to drop to zero persons/m*s. The fact that Peschl and Stapelfeldt sometimes had to abort their experiments prematurely, indicates how dangerous bulk queuing can become.

<table>
<thead>
<tr>
<th>Evacuation method</th>
<th>Capacity per meter (width) [persons/m*s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow, comfortable</td>
<td>1.2</td>
</tr>
<tr>
<td>Normal</td>
<td>2.4</td>
</tr>
<tr>
<td>Crowding, narrow door (≤ 1,20m) *</td>
<td>3.0</td>
</tr>
<tr>
<td>Crowding, wide door (&gt; 1,20m) **</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Table 9.3: Portal handling capacity of doorways per meter doorwidth per second (SBR 1984)

* Increased risk of (extreme) bulk queuing; ** Increased risk of falling down

Table 9.4 gives the portal handling capacities for different widths, assuming a ‘normal’ evacuation scenario (SBR 1984). Note that the Dutch building code requires the minimum width of a portal in an emergency egress route to be 0,85m (Bouwbesluit 2009, art. 2.167). A recent SBR publication advises door widths of 1,80m to accommodate the tendency of people to move in groups (SBR, DSP-groep 2007).

<table>
<thead>
<tr>
<th>Door opening (m)</th>
<th>1,00</th>
<th>1,10</th>
<th>1,20</th>
<th>1,30</th>
<th>1,40</th>
<th>1,50</th>
<th>1,60</th>
<th>1,70</th>
<th>1,80</th>
<th>1,90</th>
<th>2,00</th>
<th>2,10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (pers/s)</td>
<td>2,40</td>
<td>2,64</td>
<td>2,88</td>
<td>3,12</td>
<td>3,36</td>
<td>3,60</td>
<td>3,84</td>
<td>4,08</td>
<td>4,32</td>
<td>4,56</td>
<td>4,80</td>
<td>5,04</td>
</tr>
</tbody>
</table>

Table 9.4: Handling capacity of a number of door widths during ‘normal’ evacuation (SBR, 1984)

9.1.5 Calculating the emergency egress time via stairways

The Dutch SBR guideline for fire safety in tall buildings discerns two situations for the recommended calculation method of the time needed for evacuation: Free Flow and Full Flow.

**Free Flow**: in this situation the SBR simply assumes the time needed to reach the ground floor to be the travel distance divided by the pedestrian speed.

\[
T_{\text{evac}} = \frac{n_{fl} \cdot l_{st}}{v}
\]

where:
- \(T_{\text{evac}}\) = the needed time for evacuation [s]
- \(l_{st}\) = the length of a stairway for 1 floor [m]
- \(n_{fl}\) = number of floors
- \(v\) = the average pedestrian speed (on the stairs) [m/s]

**Full Flow**: it has been explained in 9.1.2 that in case of Full Flow, factors like pedestrian density and stair width become important. Both factors decide the stairway handling capacity: \(C_s = 0.83 \cdot v \cdot D \cdot W_e\) [pers/s]. The handling capacity \(C_s\) results in an evacuation time:

\[
T_{\text{evac}} = \frac{\text{Population}}{C_s \cdot n_{sf}} = \frac{n_{fl} \cdot P}{C_s \cdot n_{sf}} \quad [s]
\]

where:
- \(T_{\text{evac}}\) = the needed time for evacuation [s]
- \(C_s\) = the stairway handling capacity [persons/s]
- \(n_{sf}\) = number of stairways in the building
- \(n_{fl}\) = number of floors of the building
- \(P\) = population per floor [pers]
- \(v\) = the average pedestrian speed (in a corridor, \(v_{\text{corridor}}\) => do not use \(v_{\text{stairs}}\)) [m/s]
- \(D\) = the average pedestrian density [persons/m²]
- \(W_e\) = the effective stair width [m]
Rather than reducing the pedestrian (corridor) speed with the factor 0.83, the SBR assumes the stairway handling capacity (per meter stair width) to be 1.28 pers/m*s: this handling capacity coincides with a pedestrian speed of 0.64 m/s, which is comparable to Barney’s adopted pedestrian speed, see table 9.1.

\[(9.5) \quad T_{evac} = \frac{n_{pf} \times P}{1.28 \times W_e \times n_{st}} \quad [s]\]

9.2 Side notes and criticism concerning existing models

Note that both Fruin/Barney and the SBR assume the pedestrian speed to be constant through time. This means that the evacuation time is a linear model, see figure 9.1. The figure shows how the maximum speed of about 12 seconds per floor in Free Flow shifts to Full Flow at around 13-14 building occupants per floor per emergency stairwell. The graph increases to 60 seconds, i.e. the widely known "One minute per floor" rule.

A linear model like described in section 9.1 does not take into account that pedestrians become fatigued over time and that the chance of unforeseen events increases. Increased stress or simply the monotonous repetitive task of moving down flights of stairs may increase the risk of accidents happening over time. Somebody can have an asthma or heart attack, or can simply decide to sit down and rest for a while. Needless to say, the above influences can cause the pedestrian descent speed to drop dramatically.

Another issue raised by several sources (NIST 2005, SBR 2007, MacLennan et al 2008) is that the parameters used for pedestrian speeds don’t represent the physical capabilities of the current population. The society of many countries is ageing, obesity levels are rising and an increased number of people with physical restrictions (whether caused by physical disabilities or temporary reasons, like injuries or pregnancy) remain active, both professionally and socially. These groups should therefore be taken into account when calculating pedestrian densities and speeds.

9.2.1 Homogeneous population versus occupant characterization

A first step towards formulating a more accurate stair descent rate, as proposed by Fahy and Proulx (2001), would be to stop regarding the building population as one homogeneous entity and make use of building occupant characterisation (Boyce, 1999). Table 9.5 shows an example of a framework to describe building occupant characteristics as suggested by the Land Transport New Zealand (LTNZ, 2004).
9.2.2 Pedestrian density versus group behaviour and personal functional ability

The traditional approach described by Fruin (1985) and used in the existing models, suggests that evacuees enter the stairway from their floor and merge, causing the density to increase. The increased density slows the rate of descent, i.e. the situation shifts from a Free Flow to a Full Flow model. This approach can be termed as a macroscopic approach (MacLennan et al., 2008). Recent studies have challenged this approach (Nist, 2005; MacLennan et al., 2007; Proulx, 2006; Fujiyama, 2005) where merging behaviour is replaced by deferment, group dynamics and functional ability. These issues are not macroscopic and homogeneous, but microscopic and individual by nature (MacLennan et al., 2008).

Like population characteristics, behaviour characteristics can be taken into account to create a more accurate model. Considering the unpredictability of human behaviour however, it is important to keep the possible advantages of this approach in perspective. Furthermore, viable models of this phenomenon don’t exist yet and further research would be necessary to take this into account.

A microscopic approach will most likely result in a simulation, rather than being able to present a few simple calculation formulas. This might present a problem in respect to building legislation and the way these requirements can be described in building legislation and standards. One of the main goals in this thesis is to offer more nuanced models, but without making the user dependant on commercial (simulation) software. Building egress simulators like Elvac and Simulex can however be used to develop and validate the models.

9.2.3 Evacuation height and fatigue

Another factor that affects even young, healthy people and isn’t included in current models is the development of fatigue over time. During the evacuation of the WTC towers for example, many evacuees indicated that they were unprepared for the physical challenge and that they had to rest at least once during their descent.

Fatigue can be measured over time: once again however, the rate of decrease of a pedestrian’s speed depends on personal characteristics, like physical fitness and bodyweight. In addition, a secondary result of fatigue is the increasing chance for accidents to occur.

---

<table>
<thead>
<tr>
<th>Characteristic or Behaviour</th>
<th>Resulting in</th>
<th>Impacting upon</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>All age groups – Group Dynamics; when a group of friends form prior to descent</td>
<td>Talking between themselves, becoming distracted, becoming linked with their associate</td>
<td>Moves as a group occupying the same space, reducing descent speed as well as</td>
<td>Finnis and Walton, 2007 MacLennan et al, 2007 (Via questionnaire as part of proposed longitudinal study)</td>
</tr>
<tr>
<td>Shoe Type</td>
<td>Difficulty in footing and possibly balance</td>
<td>Reduces descent speed – remove shoes</td>
<td>Finnis and Walton, 2007</td>
</tr>
<tr>
<td>Obese – BMI &gt; 35 and waist to hip ratio &gt; 0.9</td>
<td>Greater amount of space occupied, lack of endurance/stability, fatigue, cardiac problems, breathlessness, body ellipse of 0.44 m²</td>
<td>Reduces descent speed, creates blockage in stairs less than 1100mm between handrails, reduces total height that can be evacuated</td>
<td>NIST, 2005 Proulx et al, 2006 Fahy and Proulx, 2001 Leake et al, 1991 (on walking distance)</td>
</tr>
</tbody>
</table>

…(etcetera) … … …

Table 9.5: An example of formatting occupant characterization (MacLennan et al, 2008)
9.2.4 Macroscopic versus microscopic evacuation design models

Macroscopic models like described by Fruin are the basis of the current, traditional approach in evacuation capacity design. These traditional models don’t take a number of important factors into account however: three main factors have been described in this paragraph: occupant characteristics, occupant behaviour and fatigue.

Microscopic models aim to take these individual traits into account. This provides a more accurate evacuation pattern for a designer, who can incorporate the data in his design. An important note however is that a microscopic approach, with probability factors and risk assessments, becomes complicated very quickly. Where the traditional approach provides an answer following a relatively simple, linear calculation, a microscopic approach requires a computer simulation model to calculate the evolving pattern through time.

Finally, a ‘realistic’ model provides for a more detailed answer, but it is prudent to question the value of a beautifully modelled, but complicated calculation method. Does it matter, in the end, if the optimum evacuation height is found at 10 floors or 11,72 floors? If a designer is faced with the choice to divide a 42-floor building into 2 zones of 24 floors or 3 zones of 14 floors, a more simple calculation method might suffice.

9.3 Creating a modified pedestrian stair egress model

Based on the traditional models described in 9.1 and the criticism given in 9.2, a new model is presented in this paragraph. The choice has been made to create a model that incorporates a few additional factors, but to limit this number to keep things manageable. For the same reason, calculations will be based on five-minute intervals.

9.3.1 The general (Full Flow) model

The proposed model is an adaptation of the traditional model Full Flow:

\[
T_{E,\text{stairs}} = \frac{\text{Population}}{C_s \ast n_{st}} = \frac{n_{fl} \ast P}{C_s \ast n_{st}} \quad \text{[s]}
\]

\[
C_s = (f_{fa} \ast f_{dem} \ast v) \ast D \ast (f_{r,bl} \ast W_e) \quad \text{[pers/s]}
\]

where:
- \(T_{E,\text{stairs}}\) = the needed time for evacuation (via stairs) [s]
- \(C_s\) = the stairway handling capacity [persons/s]
- \(n_{st}\) = number of stairways in the building
- \(n_{fl}\) = number of floors of the building
- \(P\) = population per floor [pers]
- \(v\) = the average pedestrian speed (in a stairway); Full Flow speed [!] [m/s]
- \(D\) = the average pedestrian density [persons/m²]
- \(W_e\) = the effective stair width [m]
- \(f_{fa}\) = fatigue factor
- \(f_{dem}\) = demographic factor
- \(f_{r,bl}\) = blockage risk factor

The equation above includes three new factors that influence the capacity of the stairway. The fatigue factor \(f_{fa}\) and the demographic factor \(f_{dem}\) influence a pedestrian’s speed, and the blockage risk factor \(f_{r,bl}\) introduces the chance of a stairwell’s effective width being reduced due to people blocking the path because they are resting, suffering from an asthma attack etcetera.

Note that \(C_s\) has become a time dependant unit because of these factors: in order to maintain a reasonably simple model, the values of the factors (and thus the handling capacity) will be divided into time frames of 5-minute intervals.
9.3.2 Redefining the model into a simulation

For calculation purposes it is necessary to redefine the model into a time-based calculation:

\[
P_{\text{TOT},t=0} = n_{f1} \times P \quad \text{[persons]}
\]

\[
P_{\text{TOT},n+1} = P_{\text{TOT},n} - C_s \times n_{st} \times \Delta t \quad \text{UNTIL } P_{\text{TOT}} \leq 0
\]

\[
C_s = \left( f_{fa} \times f_{dem} \times v \right) \times D \times \left( f_{r,bl} \times W_c \right) \quad \text{[persons/s]}
\]

where:
- \( P_{\text{TOT},t=0} \) = total building population at \( t=0 \) seconds
- \( P_{\text{TOT},n+1} \) = the total building population after one time frame
- \( \Delta t \) = the length of one time frame.

The above calculation starts at \( t=0 \). After each time interval the total population decreases, based on the capacity of the stairs. The calculation continues until \( P_{\text{TOT}} = 0 \). This creates a reasonably simple simulation, which can be run in Excel. For increased accuracy, the time frame \( \Delta t \) can be set to, for instance, 10 seconds.

9.3.3 Fatigue factor \( f_{fa} \)

The fatigue factor is reduction factor: a number between 0 and 1, which represents the reduction in speed due to fatigue. If a person’s speed drops to 80% of his normal speed after 5 minutes, \( f_{fa} \) becomes 80% of the initial speed, i.e. \( f_{fa} = 0.8 \). Figure 9.2 illustrates an example of the relative speed due to fatigue, in time frames of 5 minutes.

![Relative speed vs. fatigue factor](image)

**Figure 9.2:** The relative speed, measured in time intervals of 5 minutes

The decrease in speed as illustrated in Figure 9.2 is based on pure speculation by the author. It shows the assumption that a person will initially travel downwards at his ‘normal’ speed. After 5 minutes, the repetitive motion down the stairs will cause the person to adjust his speed to a more comfortable pace. After 15 minutes, fatigue and other factors will cause the evacuee’s speed to drop further until it reaches a new ‘balance’. Another drop has been assumed after 40 minutes. After that the speed is assumed to stabilise at a minimum of 0.4 times the initial speed.

An important note is that the abovementioned decrease rate may differ from reality. The basic concept of the way fatigue is introduced into the calculation however remains the same, and the chosen values can easily be replaced by more accurate data in the future.
Another side note is that the fatigue factor may differ when comparing Full Flow situations and Free Flow situations. One might assume that a person tires faster in Free Flow, where he or she has the space to move quickly. Although the pedestrian speed during Full Flow is lower, one must not underestimate however the necessity to stay focussed in order to stay in synch with the other evacuees as you move down the stairs. For now, the same decrease in speed is assumed in both Full Flow and Free Flow situations.

9.3.4 Demographic factor \( f_{\text{dem}} \)

The demographic factor is a constant factor, based on the average pedestrian speed of a number of archetype groups of the population. The typical population of a residential building differs from that of an office building, for example.

The demographic factor can be determined in two ways: a method considering the "weakest chain link", to be the bottleneck, and a method attempting to include the percentages of the different groups.

- The "Weakest Chain" method uses the average walking speed of the slowest group, no matter how small its percentage is in relation to the rest of the building occupants.
- The second method multiplies each typical speed of a certain group with its percentage. The summarized number is then divided by 100% * the fastest group’s speed.

For example:

\[
v = \frac{v_{\text{group1}} \times 0.23 + v_{\text{group2}} \times 0.68 + v_{\text{group3}} \times 0.09}{v_{\text{group1}} \times 1}
\]

(with assumed percentages: 0.23+0.68+0.09 = 1)

This can be rewritten as:

\[(9.10)\quad v = \frac{v_{\text{group1}} \times \%_{\text{group1}} + v_{\text{group2}} \times \%_{\text{group2}} + v_{\text{group3}} \times \%_{\text{group3}}}{100\%}
\]

(where \( \%_{\text{group1}} + \%_{\text{group2}} + \%_{\text{group3}} = 100\% \))

Neither method portrays the real situation truly accurately, but they allow for a reasonable way to include the physical capabilities of the building occupants.

One important side note is the observation that the population groups that deal with physical restrictions are often linked: elderly people have a relatively higher chance of rheumatism, people with obesity may develop diabetes, etcetera. It is therefore necessary to avoid an overlap when applying reduction factors. This is the reason for adding only one demographic reduction factor. This means that further research is needed to provide more reduction factors for the different types of building occupants possible.

The necessary demographic data is available at sources like the Dutch CBS (Centraal Bureau voor de Statistiek), or "Statistics Netherlands" in English. Statistics Netherlands is responsible for collecting and processing data in order to publish statistics to be used in practice, by policymakers and for scientific research1. This thesis will refrain from further research in this factor however, as this would require extensive research considered beyond the scope of this thesis.

\[1\] CBS site: [http://www.cbs.nl](http://www.cbs.nl)
9.3.5 Blockage risk factor $f_{bl}$

As the evacuation process progresses, the risk of a stairway being (partially) blocked increases. People sit down to rest, somebody may stumble and fall, have an asthma attack, etcetera. This factor attempts to describe the decrease in speed due to stationary people who are blocking the way; more in general, it enables the user to add a probability/risk based factor into the calculation.

The blockage risk factor consists of two parts:
- The first part takes into account the risk of occurrence. This risk gradually increases over time, as people become fatigued and lose focus.
- The second part takes into account the reduction of the effective width of the stairs caused by the blockage. Dividing $W_e$ by the reduced $W_e$ gives the relative reduction of the stair width.

\begin{equation}
(9.11) \quad f_{r,bl} = (1 - R_{bl}) \frac{W_e}{W_e - W_{bl}}
\end{equation}

with:
- $W_e$ = the effective stair width [m]
- $W_{bl}$ = Width of a blockage [m]
- $R_{bl}$ = Risk of blockage

Important note: it is necessary to include a minimum effective width. A person blocking a 900 mm wide stairway, reducing its effective width to 900-750=150mm, effectively blocks the entire stairway: others aren’t able to squeeze through a 150mm gap. This raises a question: what is the minimum effective width needed by a person?

In the Netherlands, building codes have determined 900 mm as the typical passing width of a single person: a hallway should, for example, be at least 1800 mm wide for two people to pass each other without much difficulty, not including obstructions like radiators. In this thesis, passing somebody in the emergency stairwell is assumed to require at least 600 mm. This value is based on the typical occupancy ellipse of a male, as described in the works of Fruin (1987) and Barney (2003). As illustrated in figure 9.3, 600 mm can be considered to be the occupancy space of a male, for instance while squeezing to pass a queue of people on a flight of stairs. This explains the minimum required width of emergency stairwells in Dutch legislation (1200 mm).

Fruin (1987) considers minor counterflow (caused by pedestrians moving up the stairway) to equal 750 mm (150 mm more than the typical occupancy ellipse). This value could be used to indicate the blocked width caused by one person.

The risk of blockage starts at a low value and increases over time. How this increase progresses is not yet clear. Until further studies are available, the following risk progression will be assumed over time:
Figure 9.3: Risk of blockage through time

As can be seen in Figure 9.3, the risk of blockage starts at 5% and has been assumed to increase linearly over time: every 10 minutes the risk increases by 5 percent.

There is hardly any research data available concerning the specific influence of blockages and its effects. In one example however, it has been argued that the effect of (local) blockages is marginal. After having passed the obstruction, evacuees can temporarily move faster and close the gap caused by that obstruction. This means that the egress time does not change on a macroscopic level by these temporary obstructions caused by counterflow (NIST 2005, NCSTAR 1-7, pp. 151-152). Group behaviour dynamics on the other hand could be cause for serious congestion, as explained in paragraph 9.2.2: if one member of the group sprains his ankle for instance, the entire group could slow down as they try to help keep their colleague moving along.

In general, this factor can be regarded as an attempt to introduce a risk factor into the calculation. The fatigue factor can be viewed as a decrease in performance over time, and the demographic factor is basically a correction factor that lowers the pedestrian speed to fit the relevant group of building occupants.

9.3.6 The Free Flow model

The model for Free Flow situations can be rewritten as:

\[
T_{E, \text{stairs, free}} = \frac{H_{\text{Fl}} \cdot l_{st}}{v(t)} \quad \text{[s]}
\]

\[
(9.13)
\]

with:

\[
v(t) = (f_{fa} \cdot f_{dem}) \cdot v \quad \text{[m/s]}
\]

where:

- \(T_{E, \text{stairs, free}}\) = the needed time for evacuation (via stairs, free flow) [s]
- \(l_{st}\) = the length of a stairway for 1 floor [m]
- \(n_{fl}\) = number of floors
- \(P\) = population per floor [pers]
- \(v\) = average pedestrian speed (on the stairs); \(\text{Free Flow speed} (f)\) [m/s]
- \(v_{fl}\) = current pedestrian speed at a given time (t) (on the stairs) [m/s]
- \(f_{fa}\) = fatigue factor
- \(f_{dem}\) = demographic factor
Note that, unlike the Full Flow model, the Free Flow model does not include a blockage risk factor: it is assumed that the lower pedestrian densities of the Free Flow situation allow for free passage, thus limiting the influence of possible blockage.

The Free Flow model calculates the time a person needs to get from top floor to bottom floor, so the only time-dependant factor is the fatigue factor. To simplify this calculation, the fatigue factor could be based on the building height, i.e. the number of floors and the floor height.

### 9.3.7 Portals

The evacuation time influenced by portals (namely fire-resistant doors) can be calculated using a quite simple equation:

\[
T_{E, \text{portal}} = \frac{\text{Population}}{C_p \times n_{st}} = \frac{n_{fl} \times P}{C_p \times n_{st}}
\]

where:
- \(T_{E, \text{portal}}\) = the needed time for evacuation (via portals) [s]
- \(P_{TOT,0}\) = total building population at \(t=0\) seconds
- \(C_p\) = the portal handling capacity [persons/s]
- \(n_{st}\) = number of stairways in the building
- \(n_{fl}\) = number of floors of the building
- \(P\) = population per floor [pers]

Paragraph 9.1.4 shows the portal handling capacity to be a constant factor. With no time-dependant factors, it is relatively easy to find out if portals are a possible bottleneck in the system.

### 9.3.8 Choosing between Full Flow, Free Flow and portals

The actual pedestrian traffic flow can be limited by three factors: Full Flow, Free Flow and portals. The bottleneck of the three determines the actual pedestrian flow rate. This can be noted as:

\[
T_{E, \text{stairs}} = \max \left\{ \begin{array}{ll}
\frac{n_{fl} \times P}{C_s \times n_{st}} & \text{(Full Flow)} \\
\frac{n_{fl} \times l_{st}}{v(t)} & \text{(Free Flow)} \\
\frac{n_{fl} \times P}{C_p \times n_{st}} & \text{(Portals)}
\end{array} \right. \quad \text{[s]}
\]

with:
- \(C_s\) = \(f_{fa} \times f_{dem} \times v \times D \times f_{r,bl} \times W_e\) [pers/s]
- \(v(t)\) = \(f_{fa} \times f_{dem} \times v\) [m/s]

where:
- \(T_{E, \text{stairs}}\) = the needed time for evacuation (using stairs) [s]
- \(C_s\) = the stairway handling capacity [persons/s]
- \(C_p\) = the portal handling capacity [persons/s]
- \(n_{st}\) = number of stairways in the building
- \(n_{fl}\) = number of floors of the building
- \(P\) = population per floor [pers]
- \(v_{ave}\) = the average pedestrian speed in a stairway; Full Flow speed (!) [m/s]
- \(v_{ave}\) = the average pedestrian speed on the stairs; Free Flow speed (!) [m/s]
- \(v(t)\) = current pedestrian speed at a given time \(t\) (on the stairs) [m/s]
- \(l_{st}\) = the length of a stairway for 1 floor [m]
- \(D\) = the average pedestrian density [persons/m²]
- \(f_{fa}\) = fatigue factor
- \(f_{dem}\) = demographic factor
- \(f_{r,bl}\) = blockage risk factor

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9.4 The complete pedestrian evacuation model

An evacuation is more than travelling down an emergency stairwell. Paragraph 5.4 described the successive stages of an unfolding emergency situation. This paragraph combines the above models and adds important phases of the entire evacuation process.

9.4.1 Elapsed time before reaching the emergency stairwell

There are a few phases before people actually reach the stairs. The detection and response phases are widely recognised: see paragraph 5.4.2 for both Dutch and international requirements for time frames. The SBR guideline for these time frames will be used in calculations:

- Detection time: \( T_{\text{detection}} = 13 \) minutes
- Reaction time: \( T_{\text{reaction}} = 2 \) minutes
- Pedestrian travel time to the emergency stairwell: \( T_{\text{initial}} = 30 \) seconds

9.4.2 Transfer times during evacuation

After reaching the ground floor, the evacuees still need to reach the designated “secure” area: this can be a designated area outside or a neighbouring building, for example.

In a pedestrian-only model there is no need to worry about times needed to transfer evacuees from a stairwell, through a protected lobby, into an elevator. A building may have extra transfer times however, caused for example by segmented stairwells. For clarity reasons, the model will only consider actual transfers from stairs to lifts when calculating transfer times. This means that transfer times aren’t applicable for the pedestrian egress model.

The abovementioned factors have been defined as:

- Transfer time \( T_{\text{transfer}} \): the time necessary for a transfer on floor \( x \) (not applicable in the pedestrian model).
- Reception time \( T_{\text{reception}} \): the time necessary to travel from the ground floor lobby to the designated secure area.

9.4.3 The complete pedestrian evacuation model

After introducing these additional factors, the pedestrian model becomes:

\[
T_{E,\text{stairs}} = T_{\text{detection}} + T_{\text{reaction}} + T_{\text{initial}} + \max \left( \begin{array}{c}
\frac{n_{st} \cdot P}{C_s \cdot n_{st}} \\
\frac{n_{fl} \cdot l_{st}}{v(t)} \\
\frac{n_{fl} \cdot P}{C_p \cdot n_{st}}
\end{array} \right)
\]

(9.16)

where:

- \( T_{E,\text{stairs}} \) = the needed time for evacuation (using stairs) [s]
- \( T_{\text{detection}} \) = detection time [s]
- \( T_{\text{reaction}} \) = reception time [s]
- \( C_s \) = the stairway handling capacity [persons/s]
- \( C_p \) = the portal handling capacity [persons/s]
- \( n_{st} \) = number of stairways in the building
- \( n_{fl} \) = number of floors of the building
- \( P \) = population per floor [pers]
- \( v(t) \) = current pedestrian speed at a given time (t) (on the stairs) [m/s]
- \( l_{st} \) = the length of a stairway for 1 floor [m]
- \( W_e \) = the effective stair width [m]
- \( f_{fa} \) = fatigue factor
- \( f_{dem} \) = demographic factor
- \( f_{r, bl} \) = blockage risk factor
- \( D \) = the average pedestrian density [persons/m²]

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10 INTEGRATING PEDESTRIAN AND LIFT EGRESS MODELS

This chapter will describe the merging of the pedestrian egress model formulated in chapter 9, with a lift egress model that has been developed by the Deerns engineering and consultancy company. Most existing models describe either egress via lift or via emergency stairways: this model aims to incorporate the possibility to use both means of egress. Chapter 8 described various evacuation methods: the integrated model can calculate egress times for most of these methods.

10.1 The lift egress model

This lift egress model has been developed by Deerns. Please note that Deerns owns the copyrights for this model and that the author is using it with their express permission.

The lift egress model has been based on the up peak handling capacity (UPPHC) of the lift system (as explained in paragraph 3.2). The UPPHC of a lift system is designed for the ‘normal’ situation. Additional factors take into account the increased efficiency and thus the increased transport capacity of a lift when comparing a (downwards) evacuation scenario and the normal (upwards) behaviour of traffic flows during up peak. This increase in efficiency is comparable to the down peak situation: people leave the building in groups and share the same destination, i.e. the main lobby, making lifts more efficient in down peak situations (Barney, 2003). Other factors include the fact that people will be prepared to forgo their desire for personal space during an evacuation scenario.

Note that shuttle lifts already function quite efficiently: for this reason, lift groups and shuttle lifts have separate calculation methods.

10.1.1 ‘Normal’ lift groups

The evacuation time using lifts is defined as:

\[
T_{E,\text{lift}} = T_{\text{lift,up}} \times \left( \frac{F_{\text{height}} \times F_{\text{Fractional}} \times F_{\text{Population}} \times F_{\text{lifs}}}{F_{\text{Efficiency}} \times F_{\text{load}}} \right) \quad [s]
\]

with:

\[
T_{\text{lift,up}} = \frac{100\% \times 300}{H_{5,\text{up}}} \quad [s]
\]

where:

- \( T_{E,\text{in}} \) = evacuation time via lifts
- \( T_{\text{lift,up}} \) = ‘normal’ time to fill up the entire building via lifts
- \( H_{5,\text{up}} \) = the “normal” 5-minute up peak handling capacity of the lift system [% in 5-minute interval]

The factors added in the above equation are all due to efficiency differences between normal mode and an evacuation scenario. They are as followed:

\[
F_{\text{Fractional}} = \begin{cases} 
0,1 + 0,9 \times \left( \frac{P_{\text{Floor,Evac}}}{P_{\text{Floor,normal}}} \right) & \text{if} \quad \left( \frac{P_{\text{Floor,Evac}}}{P_{\text{Floor,normal}}} \right) > 5\% \\
0,1 + 0,9 \times 5\% & \text{if} \quad \left( \frac{P_{\text{Floor,Evac}}}{P_{\text{Floor,normal}}} \right) < 5\%
\end{cases}
\]

where:

- \( P_{\text{Floor, evac}} \) = the floor population that needs to be evacuated via lift during evacuation [persons]
- \( P_{\text{Floor, normal}} \) = the floor population that needs to be evacuated via lift during evacuation [persons]
The factor $F_{\text{fractional}}$ describes the number of the building occupants of a floor that use the lifts for evacuation in respect to the total floor population. If not all people use the lifts but if some take the stairs, we speak of fractional evacuation. This makes the lifts more efficient than during normal use, where all people are assumed to use the lifts. If everybody is evacuated via lifts, this factor becomes 1 (which means that it doesn’t affect the calculation results).

\[ F_{\text{fractional}} = 0.7 + 0.3 \left( \frac{H_{\text{Low,Evac}} + H_{\text{Hi,Evac}} - H_{\text{Low,normal}}}{H_{\text{Hi,normal}}} \right) \]

where: 
- $H_{\text{Low,normal}}$ = the height of the bottom floor serviced by the lift group under normal circumstances [m]
- $H_{\text{Hi,normal}}$ = the height of the top floor serviced by the lift group under normal circumstances [m]
- $H_{\text{Low,Evac}}$ = the height of the lowest floor that needs to be evacuated via lift [m]
- $H_{\text{Hi,Evac}}$ = the height of the highest floor that needs to be evacuated via lift [m]

The factor $F_{\text{Height}}$ takes into account the difference between the range of the floors serviced by the lift group under normal conditions, and the floors serviced during evacuation. If not all floors are evacuated, the relative distance that lifts need to travel (and thus the travel time) is altered. For example: if the bottom (discharge) floor during evacuation is different than the ‘standard’ lobby, then this factor could be larger than 1, having a negative effect on the lift evacuation times.

\[ F_{\text{Population}} = \frac{N_{\text{Floor,Evac}}}{N_{\text{Floor,normal}}} \]

where: 
- $N_{\text{Floor,Evac}}$ = the number of floors that needs to be evacuated via lift [floors]
- $N_{\text{Floor,normal}}$ = the number of floors serviced by the lift group under normal circumstances [floors]

The factor $F_{\text{Population}}$ describes the ratio between the number of floors that need to be evacuated in respect to the total number of floors. This is in other words a way to factor in zoned evacuation. If the entire building is evacuated, this factor remains 1.

\[ F_{\text{Lifts}} = \frac{L_{\text{normal}}}{L_{\text{Evac}}} \]

where: 
- $L_{\text{Evac}}$ = the number of lifts available for evacuation [lifts]
- $L_{\text{normal}}$ = the total number of lifts in the lift group [lifts]

The factor $F_{\text{Lifts}}$ describes the ratio between the number of lifts used for evacuation and the total number of lifts in the lift group. If one or more ‘normal’ lifts has the dual function of fire-fighter’s lift, it may not be used by the ASS team if the fire department does not allow it. Some interest groups in the Netherlands are pushing to have fire-fighter’s lifts reserved exclusively for the fire department. Needless to say, this decrease in capacity adversely affects the evacuation time.

The last two factors are determined by the following tables:

<table>
<thead>
<tr>
<th>$F_{\text{Efficiency}}$</th>
<th>Office</th>
<th>Residential</th>
<th>Hotel</th>
</tr>
</thead>
<tbody>
<tr>
<td>If $H_{\text{Low,Evac}} \leq 0.3 \times H_{\text{Hi,Evac}}$ :</td>
<td>1.7</td>
<td>2.8</td>
<td>2.1</td>
</tr>
<tr>
<td>If $0.3 \times H_{\text{Hi,Evac}} &lt; H_{\text{Low,Evac}} \leq 0.6 \times H_{\text{Hi,Evac}}$ :</td>
<td>1.6</td>
<td>2.6</td>
<td>1.9</td>
</tr>
<tr>
<td>If $H_{\text{Low,Evac}} &gt; 0.6 \times H_{\text{Hi,Evac}}$ :</td>
<td>1.5</td>
<td>2.4</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 10.1: Possible values of factor $F_{\text{Efficiency}}$.

$F_{\text{Efficiency}}$ is a factor describing the increased efficiency that lifts have in evacuation mode in comparison to normal service. As can be seen in table (10.1), the lifts in hotels and residential buildings in particular make relatively many stops on their way up and down to collect multiple building occupants. The relatively effective method of operation during
evacuation (load to maximum at one floor, no intermediate stops) causes these lifts to therefore transport more people than what they were designed for.

<table>
<thead>
<tr>
<th>F_{car\ load}</th>
<th>Office</th>
<th>Residential</th>
<th>Hotel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,1</td>
<td>1,1</td>
<td>1,2</td>
<td></td>
</tr>
</tbody>
</table>

Table 10.2: Possible values of factor F_{car\ load}.

F_{car\ load} is another factor describing the increased efficiency that lifts have in evacuation mode in comparison to normal service. The contents of table (10.2) illustrate the assumption that people will allow themselves a bit less comfort during an evacuation scenario, so that lift cars can be loaded more efficiently. The values have been derived from the different design specifications for lifts in various building types. Lifts in hotels, for example, have been designed with the knowledge that visitors in hotels tend to value a larger comfort zone, resulting in a lower occupant load.

10.1.2 Shuttle lifts

The equations in the previous paragraph have been constructed with the assumption that the lifts need to collect building occupants from multiple floors. In evacuation scenarios 3a and 3b however, the lifts act as shuttles between the transition floor holding the assembled evacuees and the discharge floor at ground level. The equations for this shuttle scenario are different, as factors like door opening and closing times can have a significant influence on the total evacuation time.

Evacuation times for actual shuttle lifts (in buildings with a sky lobby, for instance) can be calculated using these equations as well.

This makes the total evacuation time using lifts in shuttle mode $T_{E,\ shuttles}$:

$$T_{E,\ shuttles} = n_{rt,1} \times (ATT + t_p + t_{door}) + t_{extra} = n_{rt,1} \times RTT + t_{extra} \text{ [s]}$$

The above components are defined as followed:

$$(10.8) \quad ATT = 2 \times \left( \frac{ATL + V_{lift}}{A_{lift}} \right)$$

$$(10.9) \quad ATL = \frac{H1 \times P1 + H2 \times P2 + H3 \times P3}{H1 + H2 + H3}$$

where: $ATT = \text{Average Travelling Time for a lift (1 round trip cycle, up and down)}$ [s]

$V_{\text{lift}} = \text{Lift speed}$ [m/s]

$A_{\text{lift}} = \text{Lift acceleration}$ [m/s²]

$ATL = \text{Average Travel Length (one way, up or down)}$ [m]

$H1, H2, H3 = \text{the height of transition floor 1, 2 and/or 3}$ [m]

$P1, P2, P3 = \text{the population of the zone using transition floor 1, 2, and/or 3}$ [persons]

$$(10.10) \quad C_{P,\text{lift}} = \frac{C_{W,\text{lift}}}{G_{\text{person}}}$$

where: $C_{P,\text{lift}} = \text{Maximum load capacity of the lift car (rounded down!)}$ [persons]

$C_{W,\text{lift}} = \text{Maximum weight capacity of the lift car}$ [kg]

$G_{\text{person}} = \text{Weight of 1 average individual person}$ [kg]

$$(10.11) \quad t_p = Occ_{\text{Lift}} \times t_{p,1}$$

with: $Occ_{\text{Lift}} = \frac{C_{W,\text{lift}}}{G_{\text{person}}} \times Occ\%$

where: $Occ_{\text{Lift}} = \text{Actual lift occupancy (compared to the lift's capacity, rounded down!)}$ [persons]

$Occ\% = \text{Actual lift occupancy - percentage-wise}$ [m/s]

$t_p = \text{passenger transfer time per round trip cycle}$ [s]

$t_{p,1} = \text{transfer time for 1 lift car passenger}$ [s]

---

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\[ n_{rt,1} = \frac{n_{rt}}{n_{Lift}} \] (10.13)

\[ n_{rt} = \frac{P1 + P2 + P3}{\text{Occ}_{Lift}} \] (10.14)

where:

- \( n_{rt} \) = the total number of round trips necessary for the lift group to empty the transition floor (rounded up!)
- \( n_{rt,1} \) = total number of round trips for 1 (shuttle) lift car
- \( n_{Lift} \) = number of lift cars

\[ t_{door} = t_{o+c,\text{top}} + t_{o+c,\text{bottom}} \text{ [s]} \] (10.15)

where:

- \( t_{door} \) = total door operating time per round trip cycle
- \( t_{o+c,\text{top}} \) = time needed for the lift doors to open and close at the top floor (= transition floor)
- \( t_{o+c,\text{bottom}} \) = time needed for the lift doors to open and close at the bottom floor (= ground level)

\[ t_{extra} = 2 \ast \left( \frac{V_{Lift}}{A_{Lift}} + t_{o+c,\text{top}} \right) \text{ [s]} \] (10.16)

where:

- \( t_{extra} \) = extra evacuation time: 1 last ride down, 2 extra stops
- \( t_{p,1} \) = transfer time for 1 lift car passenger

Equation (10.7) shows how the total evacuation time is calculated. First determine the average length that the lifts need to travel (ATL): combined with the lift speeds and acceleration values, this yields the average travel time for a lift (ATT) to go up and down. In order to determine the total Round Trip Time (RTT) of one cycle, one needs to add the passenger transfer times and the total door operating times: \( \text{RTT} = \text{ATT} + t_{p,1} + t_{door} \). After determining the number of people that can fit in a lift car during evacuation \( (n_{rt,1}) \), one can multiply this with the RTT to get the total evacuation time. In this case one extra last ride was added to pick up stragglers, illustrated by \( t_{extra} \).

### 10.2 Transition floors and temporary storage capacity

In order to be able to combine the stair model and the lift model, it is necessary to quantify the (possible) transition from stairs to lifts. An important part of the equation is the temporary storage capacity of the transition floors, where people leave the (segmented) emergency stairwell and wait in that floor’s (protected) lobby until they can enter a lift and resume their way down to safety. The storage capacity of these floors needs to be enough for the evacuees to assemble and wait together in a safe, responsible manner before it is their turn to take the lift down to ground level.

The number of people in the transition area can be defined as:

\[ P_{\text{transition}} = \begin{cases} C_s \ast dt \text{ (Full Flow)} \\ \frac{v(t) \ast D_{\text{free}} \ast W_e \ast dt}{C_p} \text{ (Free Flow)} \end{cases} - C_{c,\text{lift}} \ast dt \text{ [persons]} \] (10.17)

where:

- \( P_{\text{transition}} \) = the population in the transition area
- \( C_s \) = the stairway handling capacity [persons/s]
- \( C_l \) = the lift handling capacity (downwards, during evacuation) [persons/s]
- \( v(t) \) = pedestrian speed [m/s]
- \( D_{\text{free}} \) = population density in the stairway in a free flow situation [persons/m²]
- \( W_e \) = effective width of the stairway [m]

Once the building population in zone \( x \) starts moving, the protected lobby will start to fill up, beginning with the population from that very floor. The lobby is a storage vessel for the people there, with new people arriving from the emergency stairwell, and other people leaving via the lifts, following the directions of a team of appointed safety supervisors.
An important aspect is the storage capacity of the protected area at the transition floor: this area needs to be large enough to harbour the evacuees. The storage capacity should satisfy the following condition: all building occupants of the building zone (due to horizontal compartmentalisation, see paragraph 7.2.8) should be able to be accommodated in the protected area in a responsible manner, meaning that the maximum population density should not be exceeded. With this in mind, the size of the protected area on the transition floor can be defined as:

\[
A_{\text{transition}} = \frac{P \cdot n_{\text{fl, zone}}}{D_{\text{max}}}
\]

where:
- \(A_{\text{transition}}\) = the required area of the protected transition lobby \([\text{m}^2]\)
- \(P\) = the building population per floor \([\text{persons}]\)
- \(n_{\text{fl, zone}}\) = the number of floors in one building zone
- \(D_{\text{max}}\) = the maximum allowable population density in a refuge area \([\text{persons/m}^2]\)

In reality, the population at transition floor level should be able to reach the protected area within 1 minute, as the Dutch Building Code dictates. In order to keep the model manageable, the author assumed however that the protected transition area fills up according to the applicable flow rate, i.e. Free Flow, Full Flow or Portals: one of these three is the governing flow rate, as decided in equation (9.16).

### 10.2.1 Population of the transition floor in relation to handling capacities

As shown in equation (10.17), the population of the transition area depends on the stair handling capacity on one side, and the lift handling capacity on the other side. This creates two situations:

- \(C_s > C_L\):
  - The stairway handling capacity \(C_s\) is larger than the lift handling capacity (downwards, during evacuation) \(C_L\). This means that the lifts aren’t able to handle the flow of people that enter the transition area: the number of people in the transition area steadily grows, until the last building occupants have left the stairs and entered the transition area. After that, the number of people in this area decreases by the rate of the lift handling capacity:

![Diagram showing accumulation of population](image)

Figure 10.1 illustrates how the flow of pedestrians into the area first exceeds the flow of people leaving via the lifts at first. At time \(t_1\), the influx of pedestrians becomes zero (illustrated by the constant line), while the lifts steadily keep shuttling groups of people down to the ground floor; this time also marks the moment where the population of the rendezvous floor reaches its maximum. When the lines of the pedestrian flow and lift flow intersect at \(t_2\), the transition floor is empty.

The difference between the two lines corresponds with the number of people inside the transition floor. This means that the maximum amount of people in rendezvous floor
(P_{\text{max}}) can be found at time t_1. Note the possibility however that the evacuation process via the lifts may be delayed: the maximum storage capacity of the rendezvous floor should therefore be the entire population of that zone, which is higher than P_{\text{max}}.

In reality, the lift flow is not constant, as lifts come and go, transporting groups of people at a time. In this model however the lift flow has been simplified into a straight line (instead of a jagged line).

- \( C_s \leq C_L \):
The stairway handling capacity \( C_s \) is smaller than or equals the lift handling capacity (downwards, during evacuation) \( C_L \). This means that the lifts are able to handle all the people that enter the transition area as soon as they arrive.

Figure 10.2 shows how the influx of people via the stairs never causes an increase of the population of the transition floor. When people arrive, they can simply walk straight into a lift that is waiting for them. There may be a brief moment where the people arriving need to wait while all lifts are underway, but the high lift handling capacity translates into these waiting times ending when the next lift arrives.

The stairwells are empty at time \( t_1 \); after this moment the lifts will shuttle the last evacuees down to the ground floor. The graph also shows the difference in capacity between stairs and lifts through the difference between the angles of both lines (\( \Delta C \)). The handling capacity of the lifts in this case would have been fast enough to have evacuated the last person at time \( t_0 \).

10.2.2 Human behaviour in respect to rendezvous floors
The general reality is that the stairwell capacity is higher than the lift handling capacity, which corresponds to figure 10.1. As stated in section 5.5, panic situations may arise if the population inside these protected floors becomes too dense, if people see a stagnation of the evacuation flow and start to feel trapped, and that ‘bad’ signs like smoke or the sight of wounded people can act as triggers.

The average waiting time at a rendezvous floor should remain as short as possible in order to prevent a growing anxiety among the building populace: this could be achieved by demanding a higher overall lift handling capacity—which in turn demands larger investment costs. Simply allowing people the choice to continue their journey via the stairs if they wish, might already be enough to reduce the risk of panic and, at the same time, decrease the amount of people to be shuttled down via the lifts.
10.3 Combining the pedestrian and lift egress models

The models described in paragraphs 9.4 and 10.1 describe only a single travelling period. The ideal tactic for an efficient and dependable evacuation plan most likely involves a combination of both stairs and lifts. This means the model should incorporate the ability to calculate scenarios with combinations of both lift and stair egress, in order to find the ideal combination.

10.3.1 Integrating the possibility of transition floors into the model

For a single person the individual evacuation time can be modelled as:

\[ T_{\text{evac}} = T_{\text{det}} + T_{\text{reac}} + T_{\text{init}} + \max \left( T_{E,\text{stairs}} + T_{\text{trans}}, T_{E,\text{lift}} \right) + T_{\text{rec}} \]

Where:
- \( T_{E,\text{stairs}} \) = the needed time for evacuation (using stairs) [s]
- \( T_{\text{det}} \) = detection time [s]
- \( T_{E,\text{lift}} \) = the needed time for evacuation (using lifts) [s]
- \( T_{\text{reac}} \) = reaction time [s]
- \( T_{\text{trans}} \) = transition time [s]
- \( T_{\text{rec}} \) = reception time [s]
- \( T_{\text{init}} \) = initial travel time (from starting place to enclosed emergency stairway) [s]
- \( T_{\text{frac}} \) = time needed for fractional evacuation of non self-sufficient building occupants (via (fire) lifts) [s]

The evacuation time for a building is not however simply a summary of the steps that an individual evacuee goes through. When using transition floors, both stairs and lifts can be used simultaneously. Therefore the total evacuation time depends on the handling capacity of the stairways and of the lifts.

This creates two situations to consider when defining the equations describing the building evacuation time (see section 10.2.1):
- \( C_s > C_L \) : the stairway handling capacity \( C_s \) is larger than the lift handling capacity (downwards, during evacuation) \( C_L \).
- \( C_s < C_L \) : the stairway handling capacity \( C_s \) is smaller than the lift handling capacity (downwards, during evacuation) \( C_L \).

10.3.2 Proportional Fractional Evacuation

Proportional fractional evacuation is basically an effort to incorporate free will of individuals into the model. One could translate the behavioural patterns caused by individual choices into a proportion of the building population per floor: a percentage will choose to use the lifts, the rest will take the stairs. This means that the interrelation between the percentage of building occupants using the stairs and the lifts is not constant. Figure 10.3 shows a number of possible relations between people choosing to use the stairs and folks who choose to use the lifts.

![Figure 10.3: Proportional fractional evacuation. (a) linear increase caused by increase in height; (b) exponential increase; (c) spike at incident level; (d) spike + fear above incident level due to smoke visible through windows.](image-url)
The behavioural patterns illustrated in figure 10.3 are purely speculative and have no scientific research to back them up: the reason for this is that there simply is no scientific research available about such complicated patterns. It will probably be necessary to design intelligent simulation software using programming tools like neural networking and fuzzy logic, in order to map out these relations.

The variation in choice translates into a variable population per floor (P). For the (linear) pattern in figure 10.3 (a) for instance, P can be defined as:

\[
P_x = P_{st,x} + P_{li,x}
\]

\[(10.20)\]

with:

\[
P_{st,x} = P_{st,0} + \frac{P_{st,\text{top}} - P_{st,0}}{n_{fl}} \times x \quad \text{and:} \quad P_{li,x} = P_x - P_{st,x}
\]

\[(10.21)\]

Where:
- \(P_x\) = population of floor \(x\) [pers]
- \(P_{st,x}\) = stair users at floor \(x\) [pers]
- \(P_{li,x}\) = lift users at floor \(x\) [pers]
- \(P_{st,0}\) = stair users at the first floor [pers]
- \(P_{st,\text{top}}\) = stair users at the top floor [pers]
- \(n_{fl}\) = number of floors of the building
- \(x\) = floor \(x\)

Equation (10.20) states that the total population at floor \(x\) is divided into “stair users” and “lift users”. Equation (10.21) describes the linear increase of the population of each floor, from \(x = 1\) until \(x = \text{top floor}\). That linear increase lies between the minimum amount of stair user at floor 1 and the maximum amount of stair users at the top floor.

10.3.3 Sky lobbies

A sky lobby can be regarded as a special transition floor: if a building has sky lobbies, these crucial transfer floors should be designed to be secure areas and should be extremely protected by both active and passive measures. A sky lobby is a feature only found in extremely high buildings, so one could question the necessity to incorporate sky lobbies into the model (at least by Dutch standards). When assuming that the building occupants use the designated shuttle lifts for the sky lobby to continue their way downward, sky lobbies can be factored into the equation relatively easily.

The additional time needed in a sky lobby can be added to the total evacuation time using a separate calculation. It consists of two parts: arrival & waiting time (or transfer time), and the travel time to the ground floor via the shuttle lifts. One could add the transfer/waiting time in the sky lobby and the second ride using the shuttle lifts to reach ground level, into the equations described in the next paragraph.

Like with other transition floors, it is important to verify the storage capacity of the sky lobby to check if it can accommodate all building occupants of the building section that it services.

10.4 Tailoring the integrated model for six evacuation strategies

The evacuation types described in paragraph 8.1 can be translated into equations, thus allowing the evacuation times to be calculated for each evacuation type.

10.4.1 Total evacuation – stairs only

This evacuation type has been added to provide comparison between evacuation times using the current procedures, and the evacuation times of the proposed methods. The calculation model for this type is basically the complete pedestrian model described in paragraph 9.4.3:

\[
T_{\text{evac}} = T_{\text{detection}} + T_{\text{reaction}} + T_{\text{initial}} + T_{E,\text{stairs}} + T_{\text{reception}}
\]

\[(10.22)\]
\[
T_{E,\text{stairs}} = \max \left\{ \frac{n_{pi} \cdot P}{C_s \cdot n_{st}} \text{ (Full Flow)} \right\}, \quad \left\{ \frac{n_{pi} \cdot l_{st}}{v(t)} \text{ (Free Flow)} \right\}, \quad \left\{ \frac{n_{pi} \cdot P}{C_p \cdot n_{st}} \text{ (Portals)} \right\}
\]

(9.7) \quad C_s = \left( f_{fa} \cdot f_{dem} \cdot v \right) \cdot D \cdot \left( f_{r, hl} \cdot W_e \right) \quad \text{[pers/s]}

(9.13) \quad v(t) = \left( f_{fa} \cdot f_{dem} \right) \cdot v \quad \text{[m/s]}

where:
- \( T_{\text{evac}} \): total evacuation time [s]
- \( T_{\text{detection}} \): detection time [s]
- \( T_{\text{reaction}} \): reaction time [s]
- \( T_{\text{initial}} \): initial travel time (from starting place to enclosed emergency stairway) [s]
- \( C_s \): the stairway handling capacity [persons/s]
- \( C_p \): the portal handling capacity [persons/s]
- \( n_{st} \): number of stairways in the building
- \( n_{fl} \): number of floors of the building
- \( P \): population per floor [pers]
- \( v_{\text{full}} \): the average pedestrian speed (in a stairway): Full Flow speed (!) [m/s]
- \( v_{\text{free}} \): average pedestrian speed (on the stairs): Free Flow speed (!) [m/s]
- \( v(t) \): current pedestrian speed at a given time (t) (on the stairs) [m/s]
- \( l_{st} \): the length of a stairway for 1 floor [m]
- \( W_e \): the effective stair width [m]
- \( f_{\text{fa}} \): fatigue factor
- \( f_{\text{dem}} \): demographic factor
- \( f_{r, bl} \): blockage risk factor

\[
T_{E,\text{lift}} = T_{\text{detection}} + T_{\text{reaction}} + T_{\text{initial}} + T_{\text{lift,up}} \cdot \left( f_{\text{height}} \cdot f_{\text{Fractional}} \cdot f_{\text{Population}} \cdot f_{\text{lifts}} \right) + T_{\text{reception}}
\]

(10.2) \quad T_{\text{lift,up}} = 100\% \cdot 300 \text{ [s]}

where:
- \( T_{\text{lift,up}} \): ‘normal’ time to fill up the entire building via lifts [s]
- \( f_{\text{height}} \): the ‘normal’ 5-minute up peak handling capacity of the lift system [% per 5-minute interval]
- \( f_{\text{Fractional}} \): Fractional height factor
- \( f_{\text{Population}} \): Fractional population factor
- \( f_{\text{load}} \): Fractional load factor
- \( T_{\text{detection}} \): detection time [s]
- \( T_{\text{reaction}} \): reaction time [s]
- \( T_{\text{reception}} \): reception time [s]
- \( T_{\text{initial}} \): initial travel time (from starting place to enclosed emergency stairway) [s]

Note that equation (10.1b) contains additions in respect to equation (10.1), like the detection time.

10.4.3 Fractional evacuation – fire department only (constant fractional evacuation)

In this model the majority of the building occupants use the stairs for emergency egress, and only a fraction of the people use the (fire) lifts, under supervision of the fire department. These people would have great difficulty using the emergency egress stairs due to a physical limitation. They are instructed to head towards the protected lobby that contains the fire-fighter’s lift. There they need to wait for the fire department to arrive and a team to collect them, using the fire-fighter’s lift.
The evacuation can only commence after the fire department has arrived and is ready to start with the search & rescue procedure. The fire-fighter’s lift is able to stop at each floor and thus can be used to collect evacuees from all floors.

Constant fractional evacuation is based on the assumption that a fixed percentage of the building occupants use the stairs: the percentage of people using lifts is constant as well. This approach allows for a simplified calculation, where the evacuation via stairs and via lifts can be conducted separately.

\[
T_{\text{evac}} = T_{\text{detection}} + \max \left\{ \frac{T_{\text{reaction}} + T_{\text{initial}} + T_{E,\text{stairs}} + T_{\text{reception}}}{T_{\text{FDresponse}} + T_{\text{frac}} + T_{\text{reception}}} \right\} \left( \frac{n_f \cdot P}{C_s \cdot n_s} \right) \quad \text{(Full Flow)}
\]

\[
T_{E,\text{stairs}} = \max \left\{ \frac{n_f \cdot l_{u}}{v(t)} \right\} \quad \text{(Free Flow)}
\]

\[
T_{\text{lift,up}} = \frac{100\% \cdot P}{H5_{\text{up}}} \cdot 300 \quad \text{[s]}
\]

where:

- \(T_{\text{evac}}\) = total evacuation time [s]
- \(T_{\text{detection}}\) = detection time [s]
- \(T_{E,\text{stairs}}\) = the needed time for evacuation (using stairs) [s]
- \(T_{\text{reaction}}\) = reaction time [s]
- \(T_{\text{transfer}}\) = transfer time [s]
- \(T_{\text{initial}}\) = initial travel time (from starting place to enclosed emergency stairway) [s]
- \(T_{\text{reception}}\) = reception time [s]
- \(C_s\) = the stairway handling capacity [persons/s]
- \(C_p\) = the portal handling capacity [persons/s]
- \(n_s\) = number of stairways in the building
- \(n_l\) = number of floors of the building
- \(P\) = population per floor [pers]
- \(v_l\) = the average pedestrian speed (in a stairway); Full Flow speed (!) [m/s]
- \(v_{\text{avg}}\) = average pedestrian speed (on the stairs); Free Flow speed (!) [m/s]
- \(l_{u}\) = the length of a stairway for 1 floor [m]
- \(D\) = the average pedestrian density [persons/m^2]
- \(W_e\) = the effective stair width [m]
- \(f_{fa}\) = fatigue factor
- \(f_{bl}\) = blockage risk factor
- \(T_{\text{lift,up}}\) = evacuation time via lifts [s] (see paragraph (10.1.1) for definition of component factors)
- \(H5_{\text{up}}\) = the “normal” 5-minute up peak handling capacity of the lift system [% in 5-minute interval]

10.4.4 Fractional evacuation – in-house appointed safety team (constant fractional evacuation)
This fractional evacuation process assumes that a team of appointed safety supervisors collect a relatively small percentage of the building occupants, using “normal” lifts. These people would have great difficulty using the emergency egress stairs due to a physical limitation. The fire-fighter lifts remain available at all times for the fire department.
Constant fractional evacuation is based on the assumption that a fixed percentage of the building occupants use the stairs: the percentage of people using lifts is constant as well. This approach allows for a simplified calculation, where the evacuation via stairs and via lifts can be conducted separately.

\[
T_{\text{evac}} = T_{\text{detection}} + T_{\text{ASSresponse}} + T_{\text{reaction}} + T_{\text{initial}} + \max \left\{ \frac{T_{E,\text{stairs}} + T_{\text{reception}}}{T_{\text{frac}} + T_{\text{reception}}} \right\}
\]

(10.24) \] 

with: 
\[
T_{E,\text{stairs}} = \max \left\{ \frac{n_{fl} \cdot P}{C_s \cdot n_{st}} \right\} \quad \text{(Full Flow)}
\]

(9.15) \] 

\[
T_{E,\text{lift}} = \max \left\{ \frac{n_{fl} \cdot l_{st}}{v(t)} \right\} \quad \text{(Free Flow)}
\]

(10.1) \] 

\[
T_{E,\text{lift}} = \frac{F_{\text{height}} \cdot F_{\text{Fractional}} \cdot F_{\text{Population}} \cdot F_{\text{lifts}}}{F_{\text{Efficiency}} \cdot F_{\text{load}}}
\]

(9.7) \] 

where:
\[
T_{\text{evac}} = \text{total evacuation time [s]} \quad T_{\text{detection}} = \text{detection time [s]}
\]

\[
T_{E,\text{stairs}} = \text{the needed time for evacuation (using stairs) [s]} \quad T_{\text{reaction}} = \text{reaction time [s]}
\]

\[
T_{\text{initial}} = \text{initial travel time (from starting place to enclosed emergency stairway) [s]} \quad T_{\text{reaction}} = \text{response time of the team(s) of appointed safety supervisors and arrival at the first floor in need of (lift) evacuation [s]}
\]

\[
n_s = \text{the stairway handling capacity [persons/s]} \quad n_l = \text{the portal handling capacity [persons/s]}
\]

\[
P = \text{population per floor [pers]} \quad n_s = \text{number of stairways in the building}
\]

\[
v_{\text{ave}} = \text{the average pedestrian speed (in a stairway); Full Flow speed (!) [m/s]} \quad v_{\text{ave}} = \text{average pedestrian speed on the stairs; Free Flow speed (!) [m/s]}
\]

\[
v(t) = \text{current pedestrian speed at a given time (t) (on the stairs) [m/s]}
\]

\[
l_{st} = \text{the length of a stairway for 1 floor [m]} \quad D = \text{the average pedestrian density [persons/m²]}
\]

\[
W_s = \text{the effective stair width [m]} \quad f_u = \text{fatigue factor}
\]

\[
f_{\text{fa}} = \text{demographic factor} \quad f_{\text{bl}} = \text{blockage risk factor}
\]

\[
T_{\text{evac}} = \text{evacuation time via lifts [s]} \quad (\text{see paragraph (10.1.1) for definition of component factors})
\]

\[
T_{\text{lift, up}} = \text{normal’ time to fill up the entire building via lifts [s]}
\]

\[
T_{\text{H5}, up} = \text{the ‘normal’ 5-minute up peak handling capacity of the lift system [% in 5-minute interval]}
\]

10.4.5 Total evacuation – stairs – transfer floors – lifts in shuttle mode

In this model, the building is divided into sections. The lift transfer floors in the building (low-rise – mid-rise, etcetera) form the boundaries between these sections. The transfer floors act as transition floors. Note the difference:

- Transfer floor: a lift industry term, transfer from lift to lift;
- Transition floors: a term used in this thesis for the transfer from stairs to lift.

The population of one building section use the emergency stairways to reach the transition floor, which in this case equals the transfer floor. Depending on the stairway handling capacity versus lift handling capacity, the evacuees need to wait at the transition floor until they can proceed, using the lifts. These lifts are in shuttle mode and
travel directly from transition floor to ground floor and back (no response to hall calls), until the last evacuees have been collected.

Note that the possibility of a silent alarm has been added to the equation: this gives appointed supervisors the time to reach the transition floors before the general alarm is sounded \((T_{ASSresponse})\). Once the general alarm has been sounded, the first evacuees may reach the transition floor within a minute or less.

\[
\begin{align*}
T_{evac} &= T_{detection} + T_{ASSresponse} + T_{reaction} + T_{initial} + T_{E,shuttles} + T_{reception} \\
T_{evac} &= \left\{ \begin{array}{l}
C_e > C_s \Rightarrow T_{evac} = \frac{n_p \cdot P}{C_s \cdot n_{sl}} \ (\text{Full Flow}) \\
C_e \geq C_s \Rightarrow T_{evac} = \frac{n_p \cdot l_{sl}}{C_p \cdot n_{sl}} \ (\text{Free Flow}) \\
\end{array} \right. \\
\end{align*}
\]

(10.25)

\[
\begin{align*}
(C_s)_{stair} &= \max \left( \frac{n_p \cdot P}{C_s \cdot n_{sl}} \right) \\
(C_{ns})_{stair} &= \max \left( \frac{n_p \cdot l_{sl}}{C_p \cdot n_{sl}} \right) \\
\end{align*}
\]

(9.15)

\[
\begin{align*}
C_s &= \left( f_{fa} \cdot f_{dem} \cdot v \right) \cdot D \cdot l_{stair} \cdot W_e \\
v_{(i)} &= \left( f_{fa} \cdot f_{dem} \right) \cdot \bar{v} \\
\end{align*}
\]

(9.7)

where:

\[
\begin{align*}
T_{evac} &= \text{total evacuation time [s]} \\
T_{detection} &= \text{detection time [s]} \\
T_{E,stairs} &= \text{the needed time for evacuation (using stairs) [s]} \\
T_{reaction} &= \text{reaction time [s]} \\
T_{T_{shuttle}} &= \text{a single travel time of a lift in shuttle mode [s]} \\
T_{reaction} &= \text{a single travel time of a lift in shuttle mode [s]} \\
T_{T_{shuttle}} &= \text{a single travel time of a lift in shuttle mode [s]} \\
T_{t_{door}} &= \text{initial travel time (from starting place to enclosed emergency stairway) [s]} \\
T_{ASSresponse} &= \text{the response time of the team(s) of appointed safety supervisors and arrival at the first floor in need of (lift) evacuation [s]} \\
C_s &= \text{the stairway handling capacity [persons/s]} \\
C_p &= \text{the portal handling capacity [persons/s]} \\
P &= \text{population per floor [pers]} \\
n_{stair} &= \text{number of stairways in the building} \\
n_{sl} &= \text{number of floors of the building} \\
v_{(i)} &= \text{the average pedestrian speed (in a stairway): Free Flow speed [*]} \\
v_{(i)} &= \text{the average pedestrian speed (on the stairs): Free Flow speed [*]} \\
v_{(i)} &= \text{current pedestrian speed at a given time (i) (on the stairs) [m/s]} \\
l_{stair} &= \text{the length of a stairway for 1 floor [m]} \\
D &= \text{the average pedestrian density [persons/m²]} \\
f_a &= \text{fatigue factor} \\
f_b &= \text{blockage risk factor} \\
T_{E,shuttles} &= \text{evacuation time via lifts in shuttle mode [s]} \\
\end{align*}
\]

(9.13)

10.4.6 Total evacuation – stairs – transfer floors + half levels – lifts in shuttle mode

This evacuation type is basically the same as (8.1.4), with the following addition: instead of only assigning transfer floors as rendez-vous areas, an extra rendez-vous floor is assigned between the two transfer floors. For the calculation model itself, this has no impact: we can therefore use the same model as described in paragraph 10.4.5.

10.4.7 Total evacuation – stairs and lifts, free choice (proportional fractional evacuation)

This evacuation type assumes that each floor will be served by lifts during emergency evacuation: the choice between using the lift or the stairs is left up to the building occupants. Proportional fractional evacuation factors in human behaviour. It assumes that the number (or “proportion”) of the building occupants who are prepared to wait for a lift to arrive, increases with the height of their floor.

The evacuation time depends on the way the lifts service the floors (bottom-up, top-down etc.). This method is difficult to predict, as the proportion of people travelling by lift
versus stairs can vary in many different ways, see paragraph 10.3.2. This method is arguably the most chaotic one, and without proper information via monitors, for instance, there is a high risk of deviations from the model.

Providing such behavioural patterns is beyond the scope of this thesis: therefore a few important assumptions have been made:
- The lift egress system has been designed to serve every floor. In other words: on every floor the building occupants can choose to either wait for the lifts or head down via the stairs.
- The building population per floor will behave linearly, as illustrated in figure 10.1 (a). This pattern is relatively easy to describe, but still shows how and where functions describing other patterns can be implemented.
- Once a person chooses to take the stairs, he can’t change his mind. In “real life” it’s quite possible that a person who initially chose to use the stairs becomes tired and decides to use the lifts anyway, ten floors down. Advanced simulations can incorporate this example of human behaviour, but this particular model cannot take this into account without becoming a lot more complicated.

The evacuation time can be modelled as:

\[
T_{\text{evac}} = T_{\text{detection}} + T_{\text{reaction}} + T_{\text{initial}} + f(TE,\text{stairs}, TE,\text{lift}) + T_{\text{reception}}
\]

where:
- \(T_{\text{evac}}\) = total evacuation time [s]
- \(T_{\text{detection}}\) = detection time [s]
- \(T_{\text{reaction}}\) = reception time [s]
- \(TE,\text{stairs}\) = the needed time for evacuation (using stairs) [s]
- \(TE,\text{lift}\) = the needed time for evacuation (using lifts) [s]
- \(T_{\text{initial}}\) = initial travel time (from starting place to enclosed emergency stairway) [s]
- \(f(TE,\text{stairs}, TE,\text{lift})\) = a function defining the joint evacuation of lifts and stairs
- \(P_{s(h)}\) = the portion of the population per floor using the stairs, as a function of the height [pers]
- \(PL(h)\) = the portion of the population per floor using the lift, as a function of the height [pers]

The equation describing constant fractional evacuation described in paragraph 10.4.4 can’t be simply copied, due to the fact that \(P\) isn’t a constant anymore. \(P\) has become a function of the building height: it no longer simply describes the building population of that floor, but it now needs to distinguish the people that choose to use the stairs from those that use the lifts. This means that the evacuation times via stair and via lifts are no longer independent from each other.

\(f(TE,\text{stairs}, TE,\text{lift})\) is a function defining the joint evacuation of lifts and stairs. This function needs to be derived from the pattern that describes how this choice is affected. It is not possible to define this function in further detail without further research.

10.4.8 Total evacuation – stairs and lifts, free choice affected by incident level

This option is a variation of the proportional fractional evacuation model described in the previous paragraph. This model assumes that the location of the incident influences the behaviour of the building occupants, and therefore the choice of those people to take the stairs or the lift.

This translates into a different function \(f(TE,\text{stairs}, TE,\text{lift})\). Still, this function basically needs to distinguish the people that choose to use the stairs from those that use the lifts. Once this function has been determined, the evacuation time can be calculated in the same way as paragraph 10.4.8.
## 10.5 Quantifying the decision matrix using the integrated models

Using the models described in paragraph 10.4, it is possible to summarise these models in terms of the decision matrix described in chapter 8.

<table>
<thead>
<tr>
<th>Description</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Total evacuation – stairs only</td>
<td>$T_{evac} = T_{detection} + T_{reaction} + T_{initial} + T_{E,stairs} + T_{reception}$</td>
</tr>
<tr>
<td>2) Total evacuation – lifts only</td>
<td>$T_{E,lift} = T_{detection} + T_{reaction} + T_{initial} + T_{lift,up} \times \left( \frac{F_{height} \times F_{Fractional} \times F_{Population} \times F_{lifts}}{F_{Efficiency} \times F_{load}} \right) + T_{reception}$</td>
</tr>
<tr>
<td>3a) Fractional evacuation – fire department only</td>
<td>$T_{evac} = T_{detection} + \max \left{ T_{reaction} + T_{initial} + T_{E,stairs} + T_{reception} \right}$</td>
</tr>
<tr>
<td>3b) Fractional evacuation – in-house appointed safety team</td>
<td>$T_{evac} = T_{detection} + T_{ASSresponse} + T_{reaction} + T_{initial} + \max \left{ T_{E,stairs} + T_{reception} \right}$</td>
</tr>
<tr>
<td>4a) Total evacuation – stairs – transfer floors, lifts in shuttle mode</td>
<td>$C_L &lt; C_s \Rightarrow T_{evac} = T_{detection} + T_{ASSresponse} + T_{reaction} + T_{initial} + T_{E,shuttles} + T_{reception}$</td>
</tr>
<tr>
<td>4b) Total evacuation – stairs – transfer floors + half levels, lifts in shuttle mode</td>
<td>$C_L &lt; C_s \Rightarrow T_{evac} = T_{detection} + T_{ASSresponse} + T_{reaction} + T_{initial} + T_{E,shuttles} + T_{reception}$</td>
</tr>
<tr>
<td>5a) Total evacuation – stairs and lifts, free choice</td>
<td>$T_{evac} = T_{detection} + T_{reaction} + T_{initial} + f \left( T_{E,stairs}, T_{E,lift} \right) + T_{reception}$</td>
</tr>
<tr>
<td>5b) Total evacuation – stairs and lifts, free choice affected by incident level</td>
<td>$T_{evac} = T_{detection} + T_{reaction} + T_{initial} + f \left( T_{E,stairs}, T_{E,lift} \right) + T_{reception}$</td>
</tr>
<tr>
<td>6) Zoned evacuation (dependant on chosen evacuation type)</td>
<td>$T_{E,stairs} = \max \left{ \frac{n_{Fl} \times P}{C_s \times n_{st}} \right}$ (Full Flow)</td>
</tr>
<tr>
<td></td>
<td>$T_{lift,up} = \frac{100% \times 300}{H_{5,up}}$ [s]</td>
</tr>
<tr>
<td></td>
<td>$T_{E,shuttles} = n_{r,1} \left( ATT + t_p + t_{door} \right) + t_{extra} = n_{r,1} \times RTT + t_{extra}$ [s]</td>
</tr>
<tr>
<td></td>
<td>$C_s = \left( f_{fa} \times f_{dem} \times v \right) \times D \times \left( f_{r,bl} \times W \right)$ [pers/s]</td>
</tr>
<tr>
<td></td>
<td>$v' = \left( f_{fa} \times f_{dem} \right) \times v$ [m/s]</td>
</tr>
</tbody>
</table>

### Table 10.10: An overview of all evacuation models and the corresponding equations

All variables and factors described in table 10.10 are defined as followed:

- $n_{Fl}$: Number of floors
- $P$: Total population
- $C_s$: Characteristic factor
- $n_{st}$: Number of stairs
- $H_{5,up}$: Height of upstair
- $ATT$: Average time to alert
- $t_p$: Time to prepare
- $t_{door}$: Time to open door
- $t_{extra}$: Extra time
- $RTT$: Return time
- $f_{fa}$: Factor for fire alarm
- $f_{dem}$: Factor for demand
- $f_{r,bl}$: Factor for risk bl
- $W$: Weight
- $D$: Density
- $v$: Velocity
where:

- $T_{\text{evac}}$ = total evacuation time [s]
- $T_{E,\text{stairs}}$ = the needed time for evacuation (using stairs) [s]
- $T_{E,\text{lift}}$ = evacuation time via lifts [s] (see paragraph (10.1.1) for definition of component factors)
- $T_{E,\text{shuttle}}$ = evacuation time via lifts in shuttle mode [s] (see paragraph (10.1.2) for definition of component factors)
- $T_{\text{detection}}$ = detection time [s]
- $T_{\text{reaction}}$ = reaction time [s]
- $T_{\text{transition}}$ = transition time [s]
- $T_{\text{reception}}$ = reception time [s]
- $T_{\text{initial}}$ = initial travel time (from starting place to enclosed emergency stairway) [s]
- $T_{\text{shuttle}}$ = a single travel time of a lift in shuttle mode [s]
- $T_{\text{frac}}$ = time needed for fractional evacuation of non self-sufficient building occupants (via (fire) lifts) [s]
- $T_{\text{FDresponse}}$ = the fire department (total) response time, including deployment time and arrival at the first floor in need of (lift) evacuation [s]
- $T_{\text{ASSresponse}}$ = the response time of the team(s) of appointed safety supervisors and arrival at the first floor in need of (lift) evacuation [s]

- $C_s$ = the stairway handling capacity [persons/s]
- $C_l$ = the lift (group) handling capacity [persons/s]
- $C_p$ = the portal handling capacity [persons/s]
- $P$ = population per floor [pers]
- $n_{st}$ = number of stairways in the building
- $n_{fl}$ = number of floors of the building
- $v_{\text{Full}}$ = the average pedestrian speed (in a stairway): Full Flow speed (!) [m/s]
- $v_{\text{Free}}$ = average pedestrian speed (on the stairs): Free Flow speed (!) [m/s]
- $v(t)$ = current pedestrian speed at a given time (t) (on the stairs) [m/s]
- $l_s$ = the length of a stairway for 1 floor [m]
- $D$ = the average pedestrian density [persons/m$^2$]
- $W_e$ = the effective stair width [m]
- $f_{\text{fatigue}}$ = fatigue factor
- $f_{\text{demographic}}$ = demographic factor
- $f_{\text{blockage risk}}$ = blockage risk factor

- $T_{\text{lift, up}}$ = “normal” time to fill up the entire building via lifts [s]
- $H_{5,\text{up}}$ = the “normal” 5-minute up peak handling capacity of the lift system [% in 5-minute interval]
Part III

Evaluation, verification and conclusions
11 CALCULATION RESULTS USING THE DEVELOPED MODELS

In Appendix C, the different evacuation models are compared in regard to their respective evacuation times. In order to do this, a number of fictitious buildings have been "designed", providing more insight what influence design factors like the building function, population per floor and building height have on evacuation times. Using the models described in chapter 10, the evacuation times of all evacuation scenarios have been calculated.

11.1 Creating the input: the virtual buildings

In order to calculate evacuation times, one needs buildings or, more in particular, the building characteristics needed for these calculations. In this case Peutz and Deerns, the two engineering & consultancy companies where I followed my internship, created the characteristics of a number of fictitious buildings: based on these characteristics, the lift design specialist Jochem Wit (Deerns) constructed designs of a few lift configurations for each building. The building specifications have been defined according to the values given in table 11.1. These values have been chosen specifically to represent common values found in the Netherlands.

<table>
<thead>
<tr>
<th>Building function:</th>
<th>Residential</th>
<th>Hotels</th>
<th>Office buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total building height:</td>
<td>All functions: 100m, 150m, 250m.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Population per floor:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100m: 14, 20 persons</td>
<td>100m: 20 persons</td>
<td>100m: 30, 35, 40 persons</td>
<td></td>
</tr>
<tr>
<td>150m: 16, 22 persons</td>
<td>150m: 24 persons</td>
<td>150m: 32, 40, 48 persons</td>
<td></td>
</tr>
<tr>
<td>250m: 20, 24 persons</td>
<td>250m: 30 persons</td>
<td>250m: 50, 60, 70 persons</td>
<td></td>
</tr>
<tr>
<td>Floor height:</td>
<td>3,0m</td>
<td>3,3m</td>
<td>3,6m</td>
</tr>
<tr>
<td>Number of floors:</td>
<td>100m: 30 floors</td>
<td>100m: 24 floors</td>
<td>100m: 24 floors</td>
</tr>
<tr>
<td>150m: 44 floors</td>
<td>150m: 39 floors</td>
<td>150m: 37 floors</td>
<td></td>
</tr>
<tr>
<td>250m: 75 floors</td>
<td>250m: 68 floors</td>
<td>250m: 64 floors</td>
<td></td>
</tr>
<tr>
<td>Building skirt height:</td>
<td>100m: 10m</td>
<td>100m: 20,8m</td>
<td>100m: 13,6m</td>
</tr>
<tr>
<td>150m: 18m</td>
<td>150m: 21,3m</td>
<td>150m: 16,8m</td>
<td></td>
</tr>
<tr>
<td>250m: 25m</td>
<td>250m: 25,6m</td>
<td>250m: 19,6m</td>
<td></td>
</tr>
<tr>
<td>Floors (top) with half population</td>
<td>All functions: 100m: 3 floors</td>
<td>100m: 3 floors</td>
<td></td>
</tr>
<tr>
<td>150m: 4 floors</td>
<td>150m: 4 floors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250m: 6 floors</td>
<td>250m: 6 floors</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 11.1: Building specifications for the fictional building design set.

As shown above, the buildings have been categorized by their function: residential buildings, hotels and office buildings. The second main category is the building height, which is either 100, 150 or 250 meters high. This determines for each building function the number of floors and the height of the skirt of the building. High-rise buildings usually have at least one floor that serves as a general entrance, with room for a reception, loading docks, service rooms and even shopping areas: this communal area is referred to as the building “skirt”.

One important difference between numbers in the Netherlands and, for instance, the United States of America is that population values per floor are lower: this has to do with the Dutch building codes, that require that work places are situated at a maximum of 7,5 meters away from the windows (due to daylight requirements). This limits building dimensions and thus floor populations in the Netherlands.

One final and very important input value is the assumed Uppeak Handling Capacity (H5_up) of the lift systems. For residential buildings, H5_up has been set at 5%. For office buildings the value was determined at 12%, and for hotels 14%, illustrating the high standards that hotels have in order to keep their guests happy.

Appendix C lists all the input values and explains them in much more depth.
11.2 The calculation results: general remarks

Based on the input values, a number of designs have been calculated for the lift configurations. The results have been calculated for all evacuation scenario’s except scenario 4b (free choice between stairs or lifts + behaviour influenced by incident location): this scenario is too complicated for ‘straightforward’ calculations and should better be left aside for simulation programs. Scenario 4a (free choice between stairs or lifts) should technically be calculated via a simulation program as well, but a few assumptions allow for at least a rough estimate. These assumptions for scenario 4a are:

- The ratio for personal choice has been assumed to be that 50% of the occupants choose to use the stairs and 50% choose the lifts, regardless of their height in the building.
- In the stairwells the population density is low enough to allow for a Free Flow situation. This means that the (maximum) time needed to head down to safety is equal to the distance between the top floor and, in the case of this particular calculation, the skirt level of the building (in practice it should be ground level).

In general the calculation results are in the lines of the expectations: when buildings are more densely populated, congestion in the stairwells increases and evacuation times grow longer. Residential buildings and hotels have low population numbers per floor: the calculations show that for these buildings the stair egress times are relatively short (little to no congestion at all) and that therefore evacuation via lifts would actually take longer. The option of fractional evacuation to retrieve the building occupants who aren’t capable of escaping via the stairs, seems like the best option in most cases for both residential buildings and hotels.

In the case of office buildings, there appears to be a pivotal point at 150 meters where the calculated evacuation times swing in favour of using lifts. Evacuation scenario 3 in particular yields very positive results; in this scenario the building has a rendez-vous level halfway up where evacuees of the top building half assemble and wait for the lifts to shuttle them further down to safety. The stairwells now only have to accommodate half the building populace (two groups of building occupants traversing a vertical distance of maximally half the building height), which cuts the necessary stairway handling capacity in half as well. The time needed to shuttle the people in the rendez-vous level down via the lifts is a considerable factor, but at 150 meters this time becomes notably shorter compared to the traditional stairs-only method.

The following paragraphs will describe a number of specific conclusions that have been derived from the calculations. Tables with all calculation results can be found in Appendix C.

11.3 Influence of height and population density on pedestrian movement

The calculated values of the residential building models in particular showed that the stairwells simply weren’t full enough to support a Full Flow calculation: this was determined by the fact that the minimum amount of time needed to walk from the top floor to building skirt level was longer than the values derived from the capacity-based calculations.

Most of the evacuation times have been calculated using the Full Flow method: this method can basically be compared to a storage vat of which the content flows out of the tap until the vat is empty. In this analogy the content is represented by the building population and the tap is represented by the stairwell, which is assumed to be the bottleneck during evacuation. In some cases however, the storage vat would be empty in (for instance) 5 minutes, while it would take a “water droplet” or person at least 6 minutes to walk from the top floor to ground level in an empty stairwell (i.e. Free Flow).
The interpretation of this discrepancy is that the stairwells will never reach a Full Flow situation, i.e. the population density inside the stairwells will remain below 2,0 persons/m². The only reason to design two emergency stairwells in this example building is that the Dutch SBR building guideline demands at least two emergency stairwells for all buildings of this height, regardless of the building population density.

11.3.1 Visualizing the influence of height and population density

There are two main factors that define the total number of people in a building: the number of floors (in other words the building height) and the number of building occupants per floor. The data for can be visualized using the input for office buildings. The height of each floor is 3,6 meters. Table 11.2 shows the other main input values:

<table>
<thead>
<tr>
<th>Total building height</th>
<th>Skirt height</th>
<th># of floors</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 meters</td>
<td>10,4 m</td>
<td>11</td>
</tr>
<tr>
<td>100 meters</td>
<td>13,6 m</td>
<td>24</td>
</tr>
<tr>
<td>150 meters</td>
<td>16,8 m</td>
<td>37</td>
</tr>
<tr>
<td>200 meters</td>
<td>20,0 m</td>
<td>50</td>
</tr>
<tr>
<td>250 meters</td>
<td>19,6 m</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 11.2: Input values for office buildings.

Table 11.3 shows two egress times for each combination of building height and population per floor: the traditional calculation results (left) and the calculations with additional factors (right). As it isn't possible to have faster times than the Free Flow values, a number of egress times have been marked with an “FF” to indicate a Free Flow situation. In addition, a second calculation has been added for 200- and 250-meter high buildings, in which the egress times have been determined when a third emergency stairwell would be added.

The results can be visualized in a graph as shown in figure (11.1). It shows that the egress times increase linearly with the building height. When adding the proposed factors though (which have been represented by the dashed lines), the egress times increase exponentially (!). This suggests that the influence of fatigue and other speed-reduction factors will grow stronger for higher, more densely populated buildings and therefore making the option to use lifts for evacuation increasingly attractive.

In these calculations the demographic factor has been set to 1 (no influence). The other two factors start causing a longer evacuation time after 5 minutes. With this in mind, it is logical to see that the difference between the traditional and the proposed method is minimal at first: only higher buildings with larger populations start to show differences in the results. This also shows the advantages of dividing a building in sections like in scenarios 3a and 3b: the decrease in travel distance nullifies any influence caused by these factors, making the traditional calculations more dependable. In other words: if the building occupants don’t need to use the stairs all the way down from the top of (high) buildings but only need to go half way down (for instance), effects like fatigue are reduced.

When looking at the results for Free Flow (depicted by the dark blue line) and comparing it to the capacity-based egress times, it becomes clear that buildings with less than 20 occupants per floor do not have any problems with congestion in the emergency stairwells. At 30 occupants per floor the results for the traditional method are still only
marginally higher than the Free Flow situation; if factoring in the possibility of fatigue etc. though, congestion in the stairwells will become probable.

11.4 Integrating fire-fighter’s lifts in the standard lift group

In order to keep building designs as cheap as possible by minimizing the amount of lifts, many interest groups in the Netherlands are pushing for the possibility to integrate the fire-fighter’s lifts into the normal lift group. On the other side, a number of officials from fire departments demand that the fire-fighter’s lifts may only be used by fire-fighters: in case of an emergency, these lifts remain in place at ground level, reserved for the fire department: this means that these lifts can not be used by anybody else, even in the time during which the fire department haven’t arrived on scene yet. In addition the officials demand that at least two fire-fighter’s lifts should be present in the building (if one of the lifts isn’t working or has been shut down for maintenance, the fire department has a backup lift). Fire-fighter’s lifts need to service all floors, so these lifts are always either part of the central lift group or the high-rise lift group.

The combination of these three prerequisites results in a decrease of the available lifts by two. Residential lifts in particular have a relatively low building population and therefore a relatively low number of lifts. The result is quite clear when studying the tables in Appendix C: the evacuation times with central lift groups or high-rise lift groups are much higher, to the point that evacuation using lifts would be pointless for many of the building designs. Only fractional evacuation by the fire department would be a viable option in these cases.

This result could be a reason to opt for separate fire-fighter’s lifts: by using the freight/service lift(s) for a dual function as fire-fighter’s lift, the normal lift group would have at least one more lift available for ‘civilian’ evacuation. A second, more viable option would be to allow the use of fire-fighter’s lifts for ‘civilian’ evacuation in the time frame before the arrival of the fire department. With clear, unambiguous policies it should be possible to regulate properly the transition from civilian-controlled evacuation to an evacuation under supervision of the fire department.
The table below shows the comparative results for design 9, a 150-meter high office building with 48 occupants per floor (design 9a has a central lift group, design 9b has a low-rise / high-rise zone). The left column shows the ‘normal’ results, the right column shows the results when the last two lifts are allowed to be used as well.

<table>
<thead>
<tr>
<th>Design number</th>
<th>Evacuation scenario</th>
<th>Pedestrian traditional</th>
<th>Pedestrian + factors</th>
<th>Lifts</th>
<th>Bottleneck time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LR / HR</td>
<td>LR / HR</td>
<td>LR / HR</td>
<td>LR / HR</td>
</tr>
<tr>
<td>9a</td>
<td>0 – Stairs only</td>
<td>15 / 15</td>
<td>15 / 15</td>
<td>19</td>
<td>19</td>
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<tr>
<td></td>
<td>1a – Fractional (fire dpt.)</td>
<td>14 / 14</td>
<td>17 / 17</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>1b – Fractional (ASS team)</td>
<td>14 / 14</td>
<td>17 / 17</td>
<td>17</td>
<td>17</td>
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<tr>
<td></td>
<td>2 – Lifts only</td>
<td></td>
<td></td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>3a – Transfer floors</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3b – Sub-transfer floors</td>
<td>6 / 4</td>
<td>6 / 4</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>4a – Free choice lifts/stairs</td>
<td>8 / 8</td>
<td>8 / 8</td>
<td>13</td>
<td>13</td>
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<tr>
<td>9b</td>
<td>0 – Stairs only</td>
<td>15 / 15</td>
<td>15 / 15</td>
<td>9 / 19</td>
<td>9 / 19</td>
</tr>
<tr>
<td></td>
<td>1a – Fractional (fire dpt.)</td>
<td>14 / 14</td>
<td>17 / 17</td>
<td>17 / 17</td>
<td>17 / 17</td>
</tr>
<tr>
<td></td>
<td>1b – Fractional (ASS team)</td>
<td>14 / 14</td>
<td>17 / 17</td>
<td>17 / 17</td>
<td>17 / 17</td>
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<tr>
<td></td>
<td>2 – Lifts only</td>
<td>23 / 52</td>
<td>23 / 52</td>
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<td>23</td>
</tr>
<tr>
<td></td>
<td>3a – Transfer floors</td>
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<td></td>
<td>9 / 7</td>
<td>9 / 7</td>
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<td>8 / 8</td>
<td>8 / 8</td>
<td>13 / 29</td>
<td>13 / 29</td>
</tr>
</tbody>
</table>

Table 11.4: Comparative calculation results for office buildings (150m): fire-fighter’s lifts subtracted from the lift groups (left); fire-fighter’s lifts are allowed to be used (right).

When comparing the results in table 11.4, the evacuation times of especially the high-rise lift groups drop dramatically: this shows that using lifts for evacuation (other than fractional evacuation) is only viable if all lifts may be used by the ASS team, in particular for buildings with a low-rise / high-rise lift zoning method.

Even with the use of all lifts, evacuation times are only marginally shorter (with scenario 3a (3b for central lift groups) being the fastest method), at least when compared to the traditional approach. When using the additional factors, the egress time in design 9a drops from 19 to 10 minutes: in other words, the evacuation time would be cut in half.

With the results in mind, fractional evacuation might be the best evacuation method for buildings up to 150 meters, although an evacuation scenario with a rendez-vous level halfway up the building (scenario 3a/3b) has proven itself to be an alternative worth considering. Stair egress times for buildings higher than 150 meters and/or higher building populations than those chosen for these designs become high enough to warrant evacuation using lifts, making buildings with a height in the region of 100-150 meters a pivotal point in Dutch fire safety design.

In Appendix C the data can be found for all 150-meter high office buildings.

11.5 The effect of adding a third stairwell on stair egress times

All stair egress calculations have been conducted with the assumption that the building designs have 2 emergency stairwells. When regarding the increased population that makes use of the stairwells however, it is only fair to assume that, in order to meet the increased capacity needs, a third stairwell needs to be added to the design at one point. The addition of a third stairwell will affect the stair egress time: in order to both present a realistic scenario (3 stairwells) and be able to show the increasing influence of height and population density in respect to congestion for 2 stairwells, the stair egress times for both 2 and 3 stairwells have been calculated for 250-meter high office buildings.
The diagram in figure (11.2) shows how much the pedestrian egress times drop if 250-meter high office buildings are designed with a third stairwell:

Figure (11.2) shows that pedestrian egress times are reduced considerably: in particular the egress time calculated with added factors shows a huge decrease when a third stairwell is added.

Even though pedestrian egress times are reduced considerably by adding a third stairwell, these egress times are still at least twice as long as scenario 3b (with an egress time of 10-12 minutes), where a rendez-vous level has been designed halfway down the building section and the occupants are shuttled down to either the sky lobby or to ground level (depending on which building section they’re in). This shows (again) that buildings with higher population densities in particular can benefit greatly from designs that incorporate evacuation via lifts.

Please note that the egress times needed for the shuttle lift groups to evacuate the sky lobby are still applicable for these buildings and need to be added into the equation.

11.6 Shuttle lifts: a bottleneck

The lift designs of hotels and office buildings that exceed 250 meters in height typically incorporate a sky lobby that is serviced by shuttle lifts. Shuttle lifts already function quite efficiently, leaving little to no room for shorter egress times in respect to their normal service mode. The result is that, while building sections can be emptied in a time period of as short as 10 minutes, it will take much longer to shuttle down the assembled people from these sky lobbies. The calculations for the fictional buildings yielded evacuation times ranging from 43 to 52 minutes (!).

The limited handling capacity of these shuttle lifts may be a reason to reject lifts for evacuation for evacuation purposes; ironically, super-tall buildings are the main subjects of concern in the debate regarding lifts as a viable method to improve evacuation times. One of the questions that need answering is: to what extent can safety experts, building owners and officials agree about the role of sky lobbies as temporary refuge areas?

One positive aspect is that the remaining building population is concentrated in the sky lobby area: this area can be protected by robust compartments, equipped with extra
ventilation systems, communication systems, food & water or even treatment areas. During the time they need to wait for their turn to use the shuttle lifts, evacuees can be protected and tended to in this refuge area. In addition, the emergency stairwells are empty by the time the fire department arrives and are thus entirely at their disposal.

In order to create a viable evacuation scenario using lifts, solutions are required to boost the handling capacity and shorten the waiting times in the sky lobbies. One possible solution is the use of the separate service / fire fighter’s lifts to shuttle evacuees down from the sky lobby to ground level. Another possibility could be to use the lift group of the building zone below the sky lobby after this lift group has transported the last occupants of the bottom half of the building (as explained in 7.3.3).
12 TEST CASES

In order to validate the theoretical functions provided in this thesis, comparisons must be made with data collected from real life measurements regarding evacuation times, pedestrian speeds and other relevant information. In this thesis, two test cases have been singled out: the New York World Trade Center attacks, particularly the devastating attack in 2001, have provided a wealth of data. The second test case, the Delftse Poort in Rotterdam, provides an example that fits the scale and character of the Dutch building industry.

In this chapter, the building descriptions have been condensed to improve readability. Appendices A and B describe the test cases in greater detail, including information like safety measure, organisational procedures etcetera.

12.1 Test case 1: World Trade Center, terrorist attack 2001

The first terrorist attack on the World Trade Center (WTC) in 1993 and the second attack in 2001 provide two sets of data of two towers that were practically identical. The 2001 disaster in particular has been analysed and documented in detail, providing unique insight in the strengths and flaws of the building design and disaster response in respect to reality. The data regarding pedestrian traffic flows in particular provide good reference material for the pedestrian traffic model. Taking into account the height of both towers, this test case is especially valuable when attempting to determine the possible effects of fatigue when evacuating extremely tall buildings. The NIST reports (2005, 2008) in particular have formed the base of the resource data for this thesis.

12.1.1 The World Trade Center: general description

"Whether viewed from close up, from the Statue of Liberty across the Upper Bay or from an airplane descending to LaGuardia Airport, the WTC towers were a sight to behold". This observation written in the federal investigation of the World Trade Center disaster of 2001 (NIST 2005) describes quite vividly how the WTC towers were one of the main calling cards of New York. The ‘Twin Towers’ were a part of the WTC complex, which consisted of seven buildings.

Groundbreaking for the two main towers started in 1966; WTC1 (often referred to as the North Tower) was first occupied in 1970. WTC2 (also known as the South Tower) was occupied in 1972. The two main towers were almost identical in height and shape: they were both 110 floors above ground level, also referred to as the Concourse Level (NIST 2005). WTC1 was 418 meters high above ground level; WTC2 was about 416 meters high. Both towers had a square plan with dimensions 63.2*63.2 meters. WTC3 (the Marriott Hotel) was 22 floors above ground level; WTC buildings 4 and 5 were both 9 floors and WTC6 was 8 floors high. These six buildings were situated around a large plaza. Underneath the six buildings this plaza continued down into 6 subterranean levels, which included shopping malls and a

Figure 12.1: the World Trade Center, before the attack in 2001 (science.howstuffworks.com)
subway station. WTC7, a 47-floor high office building, was located across the street to the North of the plaza.

12.1.2 Account of the 2001 terrorist attack
On the morning of September 11, 2001, the World Trade Center (WTC) in New York City was attacked by hijacked commercial aeroplanes. The collision with each tower (WTC 1 at 8:46:30 a.m. and WTC 2 at 9:02:59 a.m.) produced significant structural damage (NIST 2005). The impact generated a large, luminous external fireball that consumed a portion of the jet fuel, with the remaining fuel acting as an ignition source for the combustible material within each tower. At 9:58:59 a.m., 56 minutes after it was struck, WTC 2 collapsed due to a combination of the aircraft impact damage and subsequent fire. WTC 1 stood until 10:28:22 a.m.

For the WTC towers, the times available for escape were cataclysmically established by the collapses of the buildings. Those times were not known in advance by the building occupants or the responders. The times were also considerably shorter, by a factor of three or four, than the time needed to clear the tenant spaces of WTC 1 following the 1993 bombing and an additional factor of two shorter than the time needed to clear the last person from the elevators in the building. Further, some occupants would have been unable to evacuate the buildings given any amount of time due to injuries, entrapment, and/or toxic exposure.

The Federal building and fire safety investigation of the WTC disaster was led by the National Institute of Standards and Technology (NIST 2005). NIST estimates that there were 8,900 ± 750 people in WTC 1 at 8:46:30 a.m. on September 11, 2001. Similarly, NIST estimates that there were 8,540 ± 920 people inside WTC 2 at 8:46:30 a.m. New York City officially announced 2,749 fatalities at the WTC complex, including emergency responders, airplane passengers and crew (but not hijackers), and bystanders. NIST estimated that of the 17,400 ± 1,180 occupants inside WTC 1 and WTC 2 at 8:46:30 a.m., 2,146 to 2,163 perished. No information could be found for 17 persons. More than twice as many occupants were killed in WTC 1 as WTC 2, largely due to the fact that occupants in WTC 2 used the 16 minutes between the attacks on WTC 1 and WTC 2 to begin evacuating, including the use of elevators by some occupants in WTC 2.

12.1.3 2001 attack: comparing the total pedestrian egress times
The manner in which the evacuation progresses over time, can be predicted by entering the input values into the calculation models. The results can provide an answer to one of the main questions of this thesis: which method is more accurate, the traditional method or the method with the proposed additional factors?
Plotting the calculated egress curve (for both the traditional method and the added factors) together with the observed curve for WTC1 yields the following results:

The curves in figure 12.3 show the comparative egress progressions for tower WTC1. The linear traditional method, depicted by pink curve, gives a far too optimistic egress time. The proposed method’s curve (the upper of the green curves) shows that the chosen factors slow down the expected pedestrian speeds too much.

With these results in mind, the risk blockage factor was scrapped from the equation, making only the fatigue factor an active factor. The new curve (bottom green line) appears to follow the WTC curve reasonably well; at 75 minutes the WTC curve bottoms out, but when reminded that the egress speed dropped from this moment on due to the collapse of WTC2, this difference can be explained.

Figure A.14 shows the comparative results for WTC2:
In Figure 12.4 the traditional curve more or less follows the WTC2 curve quite well, whereas the curve with the additional factors (the upper green line) displays a very low egress speed in comparison. The WTC2 data has been 'contaminated' however by the use of lifts during the 16 minutes prior to the impact of the second airplane: this explains why the WTC2 curve is relatively steep, i.e. the rate of egress was relatively fast, particularly during those first crucial 16 minutes. Even the altered curve (Bottom green line, with only the fatigue factor as active factor) proves to be too slow. Altogether it is rather difficult to draw any clear conclusions from this set of data.

One possibility would be to reset the calculations to 16 minutes, when tower 2 is hit. From this moment in time the occupants only have use of the stairs. As the evacuation is already in progress, no delay times should be added to the calculated curves. The factored curve should utilise the estimated fatigue factor at 16 minutes though, as the evacuees should theoretically already feel the effects of their journey so far. These new input values give the following results:

In figure 12.5 the traditional curve soon becomes too steep, suggesting that the egress flow in the stairwells does indeed slow down. The calculations with the fatigue factor (no blockage risk factor) still produce a curve that displays a slower egress speed in the beginning, but for a while it does run parallel to the WTC2 curve. Still the conclusion must be however that neither curve can replicate the way in which the egress speed in tower 2 progressed.

Figure 12.5: The compared egress progressions of WTC2 without the risk blockage factor, starting at the moment of impact in WTC2 (16 minutes after the impact in WTC1).

12.1.4 Evacuating the WTC towers via lifts: scenarios 3a and 3b + shuttle lifts
While the lifts were knocked out from the start in WTC1, WTC2 still had use of its lifts for 16 minutes. The NIST report (2005) states literally that the use of the lifts in WTC2 during those 16 minutes saved many lives: the question arises if even more people could have been saved if there had been an evacuation plan using the lifts.

In order to answer this question, a fictitious evacuation has been calculated for the scenarios 3a and 3b (these have proven to yield the fastest egress times in chapter 11). In addition the times were calculated in which the shuttle lifts could transport the evacuees from the skylobbies down to the Concourse level. The calculation results have been summarized in table 12.1:
Table 12.1 shows that the handling capacity of the shuttle lifts proves to be the bottleneck: this observation has been made as well in chapter 11 and in Appendix C. The calculations show that the zones in-between the skylobbies are empty within 11 minutes (maximum), after which the stairwells would have been empty; the lift capacities of the local group are sufficient to empty the rendez-vous floors with such speed that evacuees hardly need to wait at these floors (notable exception is the low zone in scenario 3b). The building occupants of both towers would have been concentrated in the skylobbies at floors 44 and 78 (and all building occupants below floor 44 would have been on the ground floor) within 11 minutes, not counting evacuation delay times.

When regarding WTC tower 2 in 2001, the calculations suggest that the 619 people who died above the impact zone would still have been alive if an evacuation system like scenario 3a or 3b had been applied for the Twin Towers. Furthermore, congestion in the stairwells would have dissolved within a maximum of 11 minutes, freeing them up for the emergency rescue services and thus speeding up the rescue operation. The skylobbies could be designed as refuge areas and even become secondary Fire Command Stations, from where the emergency services can co-ordinate their actions and tend to the evacuees while they are waiting to be shuttled down. These two observations (all building occupants accumulated in two secure areas (skylobbies) and all stairwells empty in ten minutes) are compelling arguments in favour of integrating lifts into the evacuation protocols.

However: making conclusions in hindsight should be done with caution, as every incident is different and any statements applying to one situation would be useless in a different incident. This can be demonstrated by the following observation: the impact zone where the second airliner (United Airlines Flight 175) hit WTC2, ranged from floor 78 (!) to floor 84. 12 out of 18 survivors from floor 78 and up were located on the 78th floor at the time of impact, of which one died several days later as a result of his/her injuries. This means that, had the aircraft hit the building just a few meters lower, most if not all occupants in the skylobby would have been killed. When translating this back to the evacuation scenario 3a/3b, 16/29 or 55% of the top building zone would have been shuttled down at the time of impact. 45% of that zone would have perished while waiting for the shuttle lifts, which amounts to (45% * 2706 = ) 1213 casualties. In other words: 594 more people would have been killed in this hypothetical situation.

<table>
<thead>
<tr>
<th>Input variable:</th>
<th>WTC1</th>
<th>WTC2</th>
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</thead>
<tbody>
<tr>
<td>(Building zone)</td>
<td>(low zone)</td>
<td>(mid zone)</td>
</tr>
<tr>
<td>Number of floors (total):</td>
<td>43 (0-43)</td>
<td>34 (44-77)</td>
</tr>
<tr>
<td>Number of tenant floors:</td>
<td>32</td>
<td>29</td>
</tr>
<tr>
<td>Population of the zone:</td>
<td>3222</td>
<td>2920</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3a, stairs):</td>
<td>9/11 min</td>
<td>9/9 min</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3a, lifts):</td>
<td>11 min</td>
<td>9 min</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3b, stairs):</td>
<td>8/8 min</td>
<td>7/7 min</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3b, lifts):</td>
<td>18 min</td>
<td>8 min</td>
</tr>
<tr>
<td>Estimated evacuation time (shuttles skylobby):</td>
<td>-</td>
<td>24 min</td>
</tr>
</tbody>
</table>

Table 12.1: Estimated evacuation times for WTC1 and WTC2, using the calculations in this thesis. Note that the estimated egress times include both the traditional calculation method and the method with additional factors.
12.2 Conclusions regarding the WTC test case

The 9/11 World Trade Center disaster is a compelling example of the duality of the answer to the question: “Is it beneficial to use lifts for emergency egress in tall buildings?” The calculations show that using lifts for emergency egress would shorten evacuation times significantly. The rendez-vous levels and skylobbies form natural focal points for the building officials when providing information and sending personnel to direct the evacuation process.

The flip side is that the lifts need to be functional in order for the system to work, and that the evacuation process may not dissolve into chaos if, by remote chance, the lifts do not function (i.e. backup procedures are necessary).

In the end the answer is about the level of safety that should be required by society. No building can be completely protected from extraordinary events like a terrorist attack of this magnitude. A terrorist will always target the weak spots of a building, and there will always be a chance that a severe earthquake occurs in an otherwise seismic ‘quiet’ area like the Netherlands. With this in mind, the benefits of using lifts for emergency egress outweigh the risks.

The advised evacuation protocol for the WTC towers would have been to assign local rendez-vous levels, use the local lift systems as described in scenario 3a/3b and design the two skylobbies as temporary refuge areas, where building occupants can talk among each other, gather information from emergency response personnel and receive treatment while waiting for their turn to be transported to the exit level via the shuttle lifts. In addition, each local lift group would have one lift that could serve all floors: one ASS team (Appointed Safety Supervisors) would be assigned to this lift to pick up any building occupants unable to use the stairs. Additionally, any use of the lifts would have been dependant on the ability to retrofit the building with protected lobbies etc.
12.3 Test case 2: the Delftse Poort, Rotterdam

The second test case is the Delftse Poort, an office building in Rotterdam. Until 2005 this building used to be the highest office building in the Netherlands. The Delftse Poort was built in 1991, has 41 stories and is 151 meters high (www.skyscrapercity.info). From an international perspective, this height is unremarkable. The number of buildings in the Netherlands that equal or exceed this height is increasing however: the Maastoren in Rotterdam will stand at a height of 165 meters on completion, and plans have been made to construct the Belle van Zuylen tower in Utrecht. If the latter had been realised (planned to be in 2014, plans were scrapped in January 2010 due to the economic crisis), this new tower would have been 262 meters high. In any case, the Delftse Poort presents a good representation of a Dutch office building, and is a good case study to illustrate the Dutch building environment.

12.3.1 The Delftse Poort: general description

The Delftse Poort, designed by the architect A. Bonnema, was built in 1991 (Mens 1996). The complex consists of two towers, conjoined at the bottom by a low-rise section. The first tower is 151 meters high and counts 42 floors (including the ground floor). The second tower is 93 meters high and counts 26 floors. The entire complex was designed to house 3000 employees of the Dutch insurance firm Nationale Nederlanden, which is owned by the ING Group. The complex currently houses approximately 4000 employees. The total square footage is 106,000 m² (including a restaurant and spacious conference areas), and the net office space is 66,000 m².

A.1.1 Building safety features

In case of an emergency, the Delftse Poort has an impressive array of safety features. Compared to the Dutch Building Code, these features are far superior to the minimum requirements. The reason for this is that in its time, the height of this building was unprecedented in the Netherlands. As explained in paragraph 4.1, the Dutch Building Code was (and still is) technically only valid for buildings below 70 meters; above that, building designers and city officials need to determine what an acceptable, “equality-based” solution is.

One of the most noteworthy features is the company fire brigade. This group of volunteer fire-fighters has the training, the equipment and the authority to investigate an alarm, rescue any endangered people and attack the fire.

A second noteworthy feature is the fact that the lifts have already been used for evacuation since 1991. In each tower one of the lifts serves a dual function as freight lift and fire-fighter’s lift. An intense communication and co-ordination with the fire department of Rotterdam has made it possible that the building’s ASS team is allowed to evacuate the people who cannot use the stairs via these lifts. The lift lobby is located between the two fire-resistant doors leading to the emergency stairwell, which means that the stairwell remains accessible from the lift lobby for at least 30 minutes. In
addition, the lift lobby itself can be sealed off by a fire- and smoke-resistant door, protecting the lobby for an additional 60 minutes.

On top of the fire-fighter’s lift, the building’s lift systems were equipped with an evacuation mode: personnel in the security room / Incident Command Post can switch the lifts to evacuation mode by turning a switch. However, because the current system of fractional evacuation has been deemed sufficient and because the use of lifts for evacuation still was a futuristic concept (especially in 1991!), the building officials and the fire department agreed not to use this feature.

There are more safety features, like the pressurised and compartmentalised stairwells or the backup power system: Appendix B describes the safety features that have been implemented in the Delftse Poort in detail.

12.3.2 Comparing the total pedestrian egress times
Like with the WTC test case, the remaining occupants can be predicted by entering the input values into the calculation models. The results can provide an answer to one of the main questions of this thesis: which method is more accurate, the traditional method or the method with the proposed additional factors? Plotting the calculated egress curve (for both the traditional method and the added factors) yields the following results:

![Figure 12.7: The occupancy egress progressions for the Delftse Poort (tower DP1).](image)

Figure 12.7 shows that the difference between the traditional method and the method with the factors proposed in this thesis is rather marginal. The results, which fit well into the other calculations made for 150-meter tall office buildings, are compared with the evacuation drill results in table 12.2:

<table>
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<tr>
<th>Input variable:</th>
<th>Delftse Poort DP1</th>
<th>Delftse Poort DP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evacuation time (scenario 0, stairs only) :</td>
<td>(traditional method) / (additional factors)</td>
<td>data results (drills)</td>
</tr>
<tr>
<td>Evacuation time (scenario 1, fractional) :</td>
<td>15 min / 15 min</td>
<td>16 - 17 min</td>
</tr>
</tbody>
</table>

Table 12.2: Estimated evacuation times for DP1 and DP2, using the calculations in this thesis. The stair egress times for fractional evacuation were calculated assuming a fractional evacuation of 5%. 

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The comparative results are strikingly similar: the given time frames for egress times during the drills mark more or less the area between the traditional calculation results and the results with added factors. One could therefore term this difference as the "level of uncertainty" of the necessary egress time for the Delftse Poort.

One thing to keep in mind is that the differences between the two calculation methods is still relatively small and that the real life data regarding the stair egress times isn’t exactly known (which can give room for biased interpretation of this data).

In the end though the additional factors do indeed seem to be useful: instead of outright replacing the traditional method, the combination traditional calculation and the calculation + factors appear to plot an area in which the expected egress time for a building can be found.

12.3.3 Evacuating the Delftse Poort via lifts: fractional (scenario 1a/1b) and scenario 3a

The theoretical egress times for the Delftse Poort have been calculated to show how long it would take to evacuate the office building towers using a rendez-vous level halfway up and shuttling down with lifts (scenario 3a). The calculation results have been summarized in table 12.3:

<table>
<thead>
<tr>
<th>Input variable</th>
<th>Delftse Poort DP1</th>
<th>Delftse Poort DP2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low-rise zone</td>
<td>high-rise zone</td>
</tr>
<tr>
<td>Evacuation time (scenario 0, stairs only):</td>
<td>15 / 18</td>
<td>8 / 8</td>
</tr>
<tr>
<td>Evacuation time (scenario 1, fractional, stair egress time):</td>
<td>15 / 17</td>
<td>7 / 7</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3a, stairs):</td>
<td>7</td>
<td>9 / 9</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3a, lifts):</td>
<td>~</td>
<td>18</td>
</tr>
<tr>
<td>(also using fire-fighter’s lifts for equation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3a, lifts)</td>
<td>~</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 12.3: Estimated evacuation times for DP1 and DP2. Note that the estimated stair egress times include both the traditional calculation method and the method with additional factors.

When comparing the egress times via stairs only and scenario 3a, it becomes clear that the waiting times at the rendez-vous floors are too long to provide a notable advantage. For the 151-meter high DP1 the total evacuation time would be 1 - 4 minutes shorter if all lifts are allowed to be used, but the evacuation time for DP2 (103 meters) remains too long. This coincides with the calculation results in chapter 11, which showed that scenario 3a wasn’t beneficial yet for 100-meter high buildings and that evacuation times for 150-meter high buildings became 2-6 minutes shorter, depending on the population per floor.

12.4 Conclusions regarding the Delftse Poort

The found results are in line with the calculations made in chapter 11 and Appendix C: 100-meter tall buildings are still too low to warrant any strategies other than fractional evacuation and at 150 meters a pivotal point can be seen, where the evacuation times using lifts start to become shorter.

Even the relatively high populations per floor of the Delftse Poort didn’t create notably longer evacuation times than found in the calculations of chapter 11. This could be attributed (partly) to the third stairwell in the low-rise section, the amount of floors without office space (Mechanical equipment floors etc) or perhaps that the stairwells are wider than the minimum required values, which have been used in the design calculations.

When regarding the validity of the calculation method using additional factors, the results of this test case showed that the real life data marks more or less the area
between the traditional calculation results and the results with added factors. One possibility could be to use a combination of the traditional calculation and the calculation + factors to plot an area in which the expected egress time for a building can be found.

The conclusion derived from these results is that the evacuation plan of the Delftse Poort, as existing building, should not be improved: the few minutes that could be gained by implementing rendez-vous floors would not weigh up to the cost to make the necessary alterations in the building. In addition the Delftse Poort has proven to be (almost) empty by the time the fire department arrives on scene, which means that a shorter evacuation time would provide no advantage for the rescue services. In other words: the Delftse Poort has an excellent evacuation plan and is ready for the 21st century.
13 CONCLUSIONS AND DEBATE

The research conducted in this thesis yielded a number of interesting results. From the host of literature available on the subject, the safety measures necessary to create the conditions under which emergency egress via lifts can be conducted in a safe, responsible manner, were compiled in chapter 7. A number of different strategies have been described and compared via calculations, and these calculations have been checked using real life test cases. The thesis also suggests a more nuanced way to calculate pedestrian stair egress times by using additional factors.

This chapter summarises the found results and provides recommendations for the use of lifts in the evacuation procedure.

13.1 The conditions for integrating lifts into the evacuation process

In order to make evacuation while using lifts a viable option, the functional reliability of these lifts needs to be guaranteed, at least up to an acceptable level.

Most catastrophes do not happen due to one large error, but due to a series of smaller incidents, misunderstandings and mistakes. With a good combination of physical and organisational safety features that complement each other, any unforeseen mishaps or errors can be compensated by the other safety features in place. In addition, the method of evacuation needs to be as clear and straightforward as possible in order to prevent misunderstanding and confusion among building occupants and emergency services.

13.1.1 Physical separation / compartmentation

In order to be able to use the lifts during a local incident like a fire, the lift systems and the traffic zones during emergency egress need to be physically separated from the rest of the building. Compartmentation plays a particularly important role in the safety measures needed to accomplish this: fire- and smoke-resistant doors to protect lift lobbies, emergency stairwells and lift machine rooms are an example of vertical compartmentation. Horizontal compartmentation is important for emergency stairwells, rendezvous floors and skylobbies.

Both building occupants and lift systems need to be protected, from beginning to end. Additionally systems like lift machine rooms, stairwell pressuriation/dilution systems, ventilation and communication systems and standpipes need a shell that will shield them from harm. Just as the human body protects its spinal cord, the vertical transport system of a high-rise building demands heavy protection.

13.1.2 Reliability and redundancy

Compartmentation is just one aspect of the overall reliability of the emergency egress system. The systems themselves need to be durable enough to remain functioning, even in adverse conditions. Sloped floors shouldn’t be the only measure to cope with (fire extinguishing) water: those lifts used for evacuation should be able to cope with any (small) amounts of water that happen to leak through. The fire-fighter’s lifts could be hardened to stay functional under even worse conditions.

Redundancy is another important aspect of reliability. An emergency backup generator, secondary electrical loops, battery-powered lighting, fluorescent marking, the ability of different lift groups to function separately, pressurization and dilution systems in multiple, separate locations are all forms of redundant systems backing each other up. Lift hoisting machinery can be waterproofed or different lift groups can be separated by compartmentation. Smoke can be warded from protected lobbies by pressurization, pressurization & dilution or even both combined with an extra corridor with fire-and
smoke resistant doors. Battery-powered two-way radios can be installed as a backup for the ‘normal’ communication and information systems.

In this context it is extremely important what level of security all relevant parties agree upon to be sufficient. One can state that not all lifts need to be hardened against large amounts of water flowing into and down the lift shaft, because lift lobbies have been designed with a minimal fire load (i.e. no (large) fires possible in the lift lobby), or because the landing doors have been designed to keep (sprinklered) water out of the lift shaft. If (and only due to extremely dire circumstances) the lifts are not reliable anymore compared to the required standards, the lifts should be recalled and the evacuation protocol should switch to (pedestrian) egress via the stairwells. Alternatively, the parties involved can agree to limit the usage of lifts to precautionary evacuation only, or they can agree to add an extra stairwell, for instance. In the end the choice depends on the level of safety one is willing to invest in.

The conception that passive means of fire protection are by definition better than active systems isn’t necessarily true. Chapter 5 illustrated how research has proven sprinkler systems to be more reliable than compartmentation. Any malfunctions in the lift system will be noticed soon enough during normal operation; in contrast, systems like sprinklers and compartmentation will only show their reliability after an incident occurs. The status of the lift system through time is therefore relatively easy to verify.

13.1.3 Organisation, information and communication

In every evacuation process it is crucial to have a well-functioning combination of organisation – information – communication. Both building tenant(s) and emergency services need clear, unambiguous protocols and structures, where people know what their tasks are and what they are not. The entire system should be robust enough to keep working if one or two people make a mistake or aren’t where they are supposed to be, building officials and emergency services need to coordinate their plans together and joint drills need to be conducted in order to put these plans and protocols to the test and allow the different parties to learn to work together and identify any problems.

Another crucial element is the information and communication during an incident. Building officials and emergency services need to be able to communicate properly among themselves and with other parties: any problems can be solved quickly or avoided altogether. Computers providing information regarding the building, its systems, the locations of building occupants etc. can provide a clear understanding of the situation in a short period of time, if this information is easy to access and easy to interpret. Not only personnel at the Fire Command Station (FCS) can benefit from these information nodes, but also personnel located at skylobbies and rendez-vous floors can stay informed about the situation and the way things are progressing.

Finally, information towards and communication with the building occupants is crucial in order for the evacuation process to go as planned. Information doesn’t need to be limited to marked exit paths, spoken texts over the intercom and that what the Appointed Safety Supervisors (ASS) have learned from their training. Monitors inside the protected lobbies can inform people what has happened and where, then where to go and how long it will take to get there. Interactive touch screens could be added for more and specific information. The balance between not enough versus too much information is extremely important and is a subject for future studies. Additionally, fixed points with two-way phones on floors that provide a communication line with the FCS can be of great service and a source of reassurance. ASS teams and (later on) emergency personnel situated at strategic points like rendez-vous levels and skylobbies can provide direct, face-to-face information and assistance.
13.1.4 Designing a clear egress path

While communication and information is very important, the building itself can be designed to make the egress route as clear and logical as possible, so that anybody wanting to get out, can do so almost intuitively. Placing emergency stairwells near commonly used routes will make people more aware of them as they pass them everyday. Segmenting stairwells to eject the flow of evacuees into (protected) rendezvous areas or skylobbies will steer them into the right places. Placing the entrance to the next segmented stairwell in the same compartment and in visible range to the exit of the previous one will prevent confusion and anxiety. Clear signs, markings and arrows showing the direction of the path down to safety make the egress route easy to identify. Obstructions should be kept to a minimum and the necessary ones like fire doors should have (fire-resistant) glass windows, so people can see the egress route continue on the other side.

One design feature is particularly important: the placement of at least one emergency stairwell directly next to the lift lobby. Emergency stairwells and lifts can share the protected lobbies: this saves space, reduces the necessary capacity of pressurization and/or dilution systems and allows for direct access between the two means of emergency egress. As building occupants use the lifts daily, they also are aware of the adjoining stairwell(s) next to the lift lobby, and they use the same, familiar route when in an emergency. Emergency services can look through the protected glass window of the fire door between stairwell and lift lobby to check whether the lifts are safe to use. This makes the lift lobbies the central hubs where people meet, gather information via monitors and head down to safety (while still providing enough compartmentation by the fire doors separating the lobby from the stairwell).

An ideal design should intuitively steer people into the right direction, even without additional directions from floor wardens or other people. This is yet another link, another redundancy in the emergency egress system.

13.2 The effects of lifts on the evacuation time

The calculations made in this thesis showed that lifts aren’t necessarily the fastest and most efficient solution. This paragraph will list the conclusions that have been drawn from the findings of this thesis.

13.2.1 The viability of the building evacuation scenarios

When considering the different building scenarios, it became clear which strategies worked and which did not.

Fractional evacuation, whether by the fire department or by the ASS team, is a viable option: it provides a much faster way to transport down to safety those who cannot use the stairs themselves and any local blockages inside the stairwells themselves will be reduced, improving the egress flow. As the capacity of fire-fighter’s lifts are limited though, only a very small percentage of the population (5% or less) should be evacuated via these lifts in order to keep the evacuation time manageable. This makes this scenario especially useful for high-rise buildings with relatively low populations per floor, like residential buildings or hotels. Fractional evacuation can also be used alongside scenario 3a/3b.

In buildings with floor populations above 40 persons per floor and higher than 150 meters, it becomes interesting to divide the building in sections and introduce rendezvous floors. In this context, calculations show that dividing a section in two by one rendez-vous floor (scenario 3a) yields faster results than when introducing multiple rendez-vous floors (scenario 3b). In addition, having only one rendez-vous floors means needing only one ASS team on that floor to direct people out of the stairwell and into the
lifts, which means only one team the FCS needs to communicate with, thus providing a better overview for the coordinators. Scenario 3a/3b has the additional advantage that by the time the fire department arrives, the emergency stairwells are empty and any building occupants still in the building are grouped in one area: the rendez-vous floor.

The other scenarios using lifts consume significantly more time and/or are more difficult to implement, making them undesirable compared to scenarios 1a/1b and 3a/3b.

13.2.2 The influence of the building function, building height and population/floor

When regarding the combination of building height and population per floor, the calculations have yielded a clear result: evacuation scenario 3a begins to yield faster results in buildings with floor populations above 40 persons per floor and higher than 150 meters (assuming two emergency stairwells).

The pedestrian egress time via the stairwells increases with the building’s height and floor population, while the necessary evacuation time via the lifts shuttling up to the rendezvous floor and back, stays relatively stable at between 10 – 12 minutes. This can be explained by the fact that a larger building population requires a higher total lift handling capacity in order to maintain the same total uppeak handling capacity, which means more, larger and/or faster lifts.

When regarding buildings and building functions in the Netherlands, it can be concluded that residential buildings and hotels in general do not have enough occupants per floor to warrant anything other than fractional evacuation (scenario 3a/3b). Furthermore residential buildings typically do not have ASS personnel and the response times are relatively long, making fractional evacuation conducted by the fire department (scenario 3a) the only viable option. Office buildings have relatively high floor populates, and in order to make higher buildings cost efficient, the population/floor typically increases when buildings become higher. This, in combination with the fact that all companies are required to have an ASS team, makes them suitable for evacuation scenario 4a/4b.

When buildings become so high that skylobbies become necessary, the shuttle lifts to these skylobbies become a bottleneck when evacuating using these lifts. The flipside is that more and more people will have difficulty making it all the way down when using only stairs. Designing skylobbies to function as temporary refuge areas where they can recuperate, communicate with each other and receive treatment while waiting to be shuttled down to the ground floor is a viable option (with the additional advantage that the stairwells are empty and ready to be used by emergency services). An additional option could be to use the lifts of the underlying building zone, once these (local) lifts have shuttled down the populace of their own zone (which would be after 10-12 minutes).

13.2.3 The use of additional factors in pedestrian egress calculations

Part of this thesis was dedicated to the question whether the traditional calculations used to determine pedestrian egress times could be altered to yield better, more nuanced results. While a number of simulation programs have been developed to exactly this, the proposed method using factors has the advantage that no expensive computer programs are needed, making it suitable for guidelines or even building codes.

While the calculation results and the test cases gave mixed results, the overall conclusion is that the factors do indeed appear to give better results: the real life data marks more or less the area between the (linear) traditional calculation results and the results with added factors. This implies that the expected egress time for a building lies in the plotted area between the traditional line and the curve with added factors.

The factors used in this thesis were based upon educated guesswork: the positive results found in this thesis could therefore easily be attributed to luck, rather than
scientific proof. It is therefore essential to investigate the possibility of using factors further by various simulation programs and other independent sources: after enough research it may be possible to define valid and reliable models that can be used in guidelines.

If nothing else, the use of these factors has proven that the traditional calculation method becomes increasingly unreliable when the building height and population per floor increases: therefore it does pay off to limit the vertical distance that evacuees need to traverse (and thus the influence of age, fatigue, accidents et cetera) by using the stairs, for instance by transferring the population to the lift system.

13.3 Recommendations for further research

During this thesis a number of topics have been mentioned of which additional research is required.

13.3.1 Human behaviour
The most important topic requiring further research is the modelling of human behaviour. One aspect is the collection of more empirical data from real-life incidents and experiments, in order to be able to discover the patterns that can be discerned, resulting from the different behavioural patterns that people show during the pre-evacuation stage, egress stage and possible waiting stages at rendezvous floors or refuge areas.

The second aspect is the conversion of the available data on human behaviour into simulation models. This thesis has mentioned a few times that many safety experts advocate the shift from a macroscopic to a microscopic approach, when regarding the modelling of (pedestrian) traffic flows. Using the available data on human behaviour, the programming settings of the virtual individuals can be specified. A lot of simulation runs, different configurations and even different simulation programs are necessary to filter out any biased results. The combined results of the simulation runs should provide better insight about the evacuation process. Any bottlenecks and other problems that rise to the surface can be addressed, hopefully resulting in recommendations for improvements in building safety design.

The last aspect would be to redefine any patterns found in the simulation results back to a macroscopic level. Whether by adding factors to the traditional calculation results or by offering different, better equations, the goal would be to provide a more reliable method to calculate the necessary egress time for (high-rise) buildings. This in turn could provide the basis for better norms and guidelines regarding required evacuation times, fire resistance of fire doors et cetera.

13.3.2 Safety measures
There is still a lot of additional research regarding the physical capabilities of and the potential problems surrounding all the physical safety measures that are supposed to keep the emergency egress path safe.

- The optimal method to use pressurization and/or dilution systems in the protected lobby, the stairwells and lift shafts is a good example of research regarding the different safety measures.
- An in-depth research to provide more insight of the usefulness of safety measures in terms of risk reduction. This can lead to a better understanding of the balance between the costs and benefits of different combinations of these safety measures.
- Research in the field of software programs. On one side lies the integration of all the input from sensors, cameras et cetera. The output in the form of information and communication systems needs to be a useful tool that provides that what the different parties need, without overwhelming them in an ‘information overdose’. If
properly designed, it could reduce radio traffic and make the tasks easier for all parties involved.

In general there are many opportunities for additional research to verify and combine the safety measures needed to provide an acceptable level of safety, in order to enable the use of lifts for emergency egress.
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Bukowski, R.W. *Emergency Egress from Ultra Tall Buildings*. CTBUH 8th World Congress 2008, Dubai, United Arab Emirates.


(official building codes and norms)


Bouwbesluit art. 2.135 lid 2 (in gebouwen >50m is een rooksluis verplicht)

Bouwbesluit 2009

Brandveiligheidsconcept kantoorgebouwen en onderwijsgebouwen; Bijlage G: berekeningsmethode voor de ontruiming van de ontruimingstijden bij brand.


EN81-72: Safety rules for the construction and installation of lifts - Part 72: Firefighters lifts, CEN.

EN81-73: Safety rules for the construction and installation of lifts - Part 73: Behaviour of lifts in the event of fire, CEN.

Regeling Bouwbesluit 2003; afdeling 3.1: opvang- en doorstroomcapaciteit van een vluchtrappenhuis.


Toelichting Regeling Bouwbesluit 2006

Websites

http://www.ansi.org
The website of the American National Standards Institute (ANSI). This site provides standards for U.S. building legislation. In addition it is a huge resource for updates and publications.

http://shop.bsigroup.com
The website of the British Standards Institution (BSI) online shop. Here one can purchase all British Standards (BS). The website also sells relevant literature and provides excellent cross-references to comparable European and ISO standards.

http://www.communities.gov.uk/planningandbuilding/buildingregulations
This website provides access to the official British Building Regulations. Being government legislation, they can be downloaded free of charge.

www.fema.gov
The website of the U.S. Federal Emergency Management Agency (FEMA). The research regarding the WTC 2001 disaster can be found here: http://www.fema.gov/rebuild/mat/wtcstudy.shtm

http://www.iccsafe.org
The website of the International Code Council (ICC). This organisation publishes the International Building Codes (IBC).

www.iso.org
The website of the International Organization for Standardization (ISO). Besides the ISO standards themselves, the site provides a host of information and publications.

http://jfs.sagepub.com
Website of the Journal of Fire Sciences. Registration is necessary to gain access to publications.

http://www.nfpa.org
The website of the National Fire Protection Association (NFPA). This site provides standards for U.S. building legislation. In addition it is a huge resource for updates and publications.

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http://www.skyscrapercity.info
A site that is dedicated to high-rise buildings and provides detailed information about these buildings.

http://www.top010.nl
A site dedicated to various top 10 lists in Rotterdam. One of these lists includes the three highest buildings in the Netherlands.
Appendices
Appendix A

Test case 1; World Trade Center, 2001
TEST CASE 1; WORLD TRADE CENTER, 1993 AND 2001

In order to check the validity of the models described in the previous chapters, a number of test cases are necessary. This chapter describes the attacks on the World Trade Center (WTC) in New York in 1993 and in 2001. The first terrorist attack on the WTC in 1993 and the second attack in 2001 provide two sets of data of two towers that were practically identical. The 2001 disaster in particular has been analysed and documented in detail, providing unique insight in the strengths and flaws of the building design and disaster response in respect to reality. The data regarding pedestrian traffic flows in particular provide good reference material for the pedestrian traffic model. Taking into account the height of both towers, this test case is especially valuable when attempting to determine the possible effects of fatigue when evacuating extremely tall buildings.

Fahy and Proulx (1998) published a detailed research regarding human behaviour during the 1993 attack, and a number of official investigations have documented the chain of events during the 2001 tragedy (Building Performance appraisal team 2002, NIST 2005). Large parts of the information in this chapter have been taken from, in particular, the 2005 NIST report.

A.1 World Trade Center: general description

"Whether viewed from close up, from the Statue of Liberty across the Upper Bay or from an airplane descending to LaGuardia Airport, the WTC towers were a sight to behold". This observation written in the federal investigation of the World Trade Center disaster of 2001 (NIST 2005) describes quite vividly how the WTC towers were one of the main calling cards of New York. The 'Twin Towers' were a part of the WTC complex, which consisted of seven buildings.

Groundbreaking for the two main towers started in 1966; WTC1 (often referred to as the North Tower) was first occupied in 1970. WTC2 (also known as the South Tower) was occupied in 1972.

The two main towers were almost identical in height and shape: they were both 110 floors above ground level, also referred to as the Concourse Level (NIST 2005). WTC1 was 418 meters high above
ground level; WTC2 was about 416 meters high. Both towers had a square plan with dimensions 63.2*63.2 meters. WTC3 (the Marriott Hotel) was 22 floors above ground level; WTC buildings 4 and 5 were both 9 floors and WTC6 was 8 floors high. These six buildings were situated around a large plaza. Underneath the six buildings this plaza continued down into 6 subterranean levels, which included shopping malls and a subway station. WTC7, a 47-floor high office building, was located across the street to the North of the plaza.

Figure (A.3) shows a typical floor plan of the WTC towers 1 and 2, and table A.2 shows the use of the floors, which was similar but not identical in the two towers:

<table>
<thead>
<tr>
<th>Floor(s)</th>
<th>WTC1</th>
<th>WTC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>Roof Antenna space and window washing equipment</td>
<td>Outdoor observation deck and window washing equipment</td>
</tr>
<tr>
<td>110</td>
<td>Television studios</td>
<td>Mechanical equipment</td>
</tr>
<tr>
<td>108, 109</td>
<td>Mechanical equipment</td>
<td>Mechanical equipment</td>
</tr>
<tr>
<td>107</td>
<td>Windows on the World</td>
<td>Indoor observation deck</td>
</tr>
<tr>
<td>106</td>
<td>Catering</td>
<td>Tenant space</td>
</tr>
<tr>
<td>79 through 105</td>
<td>Tenant space</td>
<td>Tenant space</td>
</tr>
<tr>
<td>78</td>
<td>Sky lobby, tenant space</td>
<td>Sky lobby, tenant space</td>
</tr>
<tr>
<td>77</td>
<td>Tenant space</td>
<td>Tenant space</td>
</tr>
<tr>
<td>75, 76</td>
<td>Mechanical equipment</td>
<td>Mechanical equipment</td>
</tr>
<tr>
<td>45 through 74</td>
<td>Tenant space</td>
<td>Tenant space</td>
</tr>
<tr>
<td>44</td>
<td>Sky lobby, kitchen, tenant space</td>
<td>Sky lobby, tenant space</td>
</tr>
<tr>
<td>43</td>
<td>Cafeteria</td>
<td>Tenant Cafeteria</td>
</tr>
<tr>
<td>41, 42</td>
<td>Mechanical equipment</td>
<td>Mechanical equipment</td>
</tr>
<tr>
<td>9 through 40</td>
<td>Tenant space</td>
<td>Tenant space</td>
</tr>
<tr>
<td>7, 8</td>
<td>Mechanical floors</td>
<td>Mechanical floors</td>
</tr>
<tr>
<td>Concourse through 6</td>
<td>6-story lobby</td>
<td>6-story lobby</td>
</tr>
</tbody>
</table>

Table A.1: Use of floors in the WTC towers (NIST 2005).

The Port Authority of New York and New Jersey (PANYNJ) had managed the operation of the two towers since their opening three decades earlier. Silverstein Properties acquired a 99-year lease on the towers in July 2001.

At the beginning of the workday, many of the roughly 40,000 people who worked in the towers and visited to tour or to conduct business emerged from PATH trains in the massive subterranean station. They would take escalators and lifts to a large shopping concourse. Walking a few hundred feet led occupants to the spacious, 6-story-high lobby on the Concourse Level where they would cross paths with those who arrived on foot or by bus and cab. The WTC 1 and WTC 2 lobbies were at the same level as the underground shopping mall, often collectively referred to as the Concourse Level. The WTC outdoor plaza and the WTC 1 and WTC 2 Mezzanine were one story higher than the Concourse Level, often referred to as either the Mezzanine or plaza level.

Many of the floors had but a single tenant, and some of these tenants occupied multiple floors. By 2001, most of these companies, which had moved in since the installation of automatic sprinklers, had taken advantage of Yamasaki's design concept of a vast space that was virtually obstruction-free. The open landscaping included as many as...
200 or more individual workstations, often clustered in groups of six or eight. Trading
floors had arrays of long tables with multiple computer screens. Some of these floors
had a few executive offices in the corners and along the perimeter. Many also had
walled conference rooms. It was common for the multiple-floor tenants to have installed
device stairs internal to their space.

Other floors were subdivided to accommodate as many as 20 firms. Some of the smaller
firms occupied space in the core area, reclaimed as lift shaft space from local lifts was
phased out throughout the towers.

With so many workers and visitors in the buildings, there needed to be food available.
The Port Authority maintained a cafeteria on the 43rd floor of WTC 1. A number of the
companies maintained kitchen areas where catered food was brought in daily, making it
unnecessary for their staff even to leave their floor for lunch. The underground
Concourse Level mall also provided many options for eating. In addition, there were
hundreds of restrooms, in both the tenant and the core spaces.

A.1.1 Vertical transportation

Getting thousands of people from the ground level to the offices, observation levels, and
restaurants, some as high as a quarter-mile, was no small task. Thus, lifts were the
primary mode of movement between floors of the World Trade Center. The World Trade
Center complex contained more than 240 lifts, with 99 lifts serving the above-ground
levels in each of the two main towers and an additional 7 lifts serving primarily the sub-
ground basement levels. In the towers, the lifts were arranged to serve the buildings in
three sections divided by sky lobbies, which served to
distribute passengers among express and local lifts.
Figure (A.4) shows a lift riser diagram for WTC 1 and
WTC 2 for passenger lifts.

- People traveling to floors 9 through 40 entered a
bank of 24 local lifts at the Concourse Level.
These were divided into four groups, with each
stopping at a different set of eight or nine floors (9
through 16, 17 through 24, 25 through 31, and 32
through 40).
- Those going to floors 44 through 74 took one of
eight express lifts to the 44th floor sky lobby
before transferring to one of 24 local lifts. These
24 were stacked on top of the lower bank of 24,
providing additional transport without increasing
the occupied floor space.
- Those going to floors 78 through 107 took one of
ten express lifts from the Concourse Level to the
78th floor before transferring to one of 24 local
lifts. These were also stacked on the lower banks
of 24.
- Dedicated express lifts served the restaurant,
bars, and meeting rooms on floors 106 and 107 of
WTC 1, as well as the observation deck in WTC 2.

An occupant traveling to the 91st floor, for example,
would have taken an express lift from the lobby to the 78th floor and then would have
had to transfer to another lift to arrive at the 91st floor. The trip would have taken several
minutes travel time, depending upon the wait at the lift lobby. While providing an acceptable rate of people movement, this three-tier system also used less of the building footprint than the usual systems in which all lifts run from the entrance to the top of the building. Further, lettable floor space was reclaimed near the top of a given zone. At the top of each lift bank, the machinery to lift the lift cars occupied the next higher floor. From the next higher floor up to the bottom of the next lift bank, there was no need for a lift shaft. The concrete floor was extended into this space, providing additional lettable floor area for offices, conference rooms, storage, etc. Assuming $55 per ft² per year as a rental rate for a downtown Manhattan office building over 600,000 ft² (BOMA 2001), the reclamation could theoretically yield nearly $6 million per year of rental income. At the time WTC was built, the concept of sky lobbies, served by express lifts and serving only one zone of the building, was innovative. Nowadays, many tall buildings use this concept.

A.2 Building safety features

This paragraph will describe building safety features like the emergency egress stairwells in more detail. Special attention is given to the transfer hallways in particular (used to lead the escape route around the huge machinery on the mechanical equipment levels).

A.2.1 Emergency stairwells

WTC 1 and WTC 2 each had three primary stairwells designed for emergency egress, designated as A, B, and C. Stairwells A and C were 1.1 m (44 in.) wide and extended from floor 2 (plaza or Mezzanine Level) to floor 110 (lower mechanical space). The stairwell landings by the exit door were 92 in (2.3 m) wide by 78 in (2.0 m) deep. Figure A.5 shows a 44 in. (1.1 m) stairwell in WTC 1 taken on September 11, 2001, by John Labriola during his evacuation. Note the photoluminescent paint on the stair edge and landing. Stairwell B was 56 in. (1.4 m) wide and ran from the subgrade 6 levels below ground to floor 107 including the Concourse (main lobby); there was no exit from Stairwell B onto the 2nd floor (plaza / Mezzanine Level). The stairwell landings by the exit door for Stairwell B were 116 in (2.9 m) wide by 78 in (2.0 m) deep. The 1968 NYC Building Code has requirements for the number and capacity of stairs and for the assumed occupant load that are similar to requirements in the other contemporaneous codes (NIST NCSTAR 1-1, Appendix A). Codes of that time required that multiple stairs be located “as remote from each other as practicable.” NYC permitted scissor stairs, and the code required the exit doors to be at least 4.6 m (15 ft) apart. Local Law 16 (1984) first imposed a remoteness requirement of 30 ft or one-third the maximum travel distance of the floor (whichever is greater). This requirement was not retroactive, so it did not apply to WTC 1 and WTC 2. However, this requirement did apply to WTC 7.
A.2.2 Transfer hallways

The WTC 1 and WTC 2 stairwells were occasionally routed horizontally around equipment on mechanical floors, through what were called transfer hallways, as shown in Figure A.6.

Stairwell B required a horizontal transfer at floor 76. For all other floors, stairwell B maintained vertical alignment through the building. Stairwells A and C required horizontal transfers (some longer than others) at floors 42, 48, 66, 68, 76, and 82. Horizontal transfer distances ranged from several feet (floors 66 and 68) to over 100ft (33 m), including smoke doors (which were closed but not locked) and multiple right angles turns in the transfer on floors 42, 48, 76, and 82 for Stairwells A and C. Note that the mechanical floors were located on floors 41-42, 75-76, and 108-109.

One problem with the horizontal transfers was that they extended the total evacuation time, when compared to a similar design without horizontal transfers. The World Trade Center Review Committee, formed by the New York City Building and Fire Commissioners in response to the 1993 WTC Bombing, found that “the occupants of the towers encountered changes in the path of egress that were unfamiliar, [contributing] to the general confusion during the evacuation process (New York City 1995).” Figure (A.7a) shows a photograph of a horizontal transfer hallway in WTC 1 or WTC 2 taken after the 1993 bombing, including photoluminescent markings.

Each stairwell had signage on both sides of the stairwell access doors indicating the letter designation of the particular stairwell. A sign on the inside of the stairwell indicated the floor number, the stairwell designation, and whether the floor was a “re-entry” or “non-re-entry” floor. Figure (A.7b) shows a photograph of this signage taken after the 1993 bombing. A non-re-entry floor was a landing in the stairwell where the door to the floor was locked from the stairwell side. If the particular floor was not a re-entry floor, the sign indicated the location of the nearest reentry location, every fourth floor (in the case of Figure (A.7b), floors 74 and 78). The stairwell doors were required to be always open every fourth floor by the NYC Building Code. Door locks leading to mechanical spaces and the roof were controlled electronically at the Security Command Center (SCC) on floor 22. The NYC Building Code also required that, in the event of a power outage, the re-entry locking mechanism would default to the open position.
A.2.3 Compartmentation

The design of WTC 1 and WTC 2 featured large, open office spaces devoid of columns due to the innovative structural design. Tenants could (and often did) utilize open plan office layouts that permitted impressive views of the Manhattan skyline out the perimeter windows.

The NYC Building Code and PANYNJ practice required partitions to separate tenant spaces from one another and from common spaces such as the corridors that served the elevators, stairs, and other common spaces in the building core. Another influence on compartmentation of the buildings was the adoption of Local Law 5 (New York 1973) (LL 5) amending the NYC Building Code. While it did not (legally) apply to the WTC buildings, PANYNJ policy was to follow the requirements voluntarily. LL 5 required compartmentation of unsprinklered spaces in existing office buildings over 100 ft in height “having airconditioning and/or mechanical ventilation systems that serve more than the floor on which the equipment is located” to be subdivided by 1 h fire separations into spaces or compartments not to exceed 7,500 ft². Floor areas could be increased up to 15,000 ft² if protected by 2 h fire resistive construction and smoke detectors. Regardless of the floor area, compartmentation is not required when complete sprinkler protection is provided (LL 5, Section 6).

Following the 1975 fire a fire safety consultant report recommended to PANYNJ that the buildings be retrofitted with sprinklers to address possible smoke problems, which would also obviate the need for compartmentation and permit the unobstructed views for which the buildings were known. The decision left the interior WTC floor arrangements with only partitions separating tenant spaces from one other and from exit access corridors or common spaces in the core, and with shaft enclosures.

A.2.4 Lifts during emergencies

The requirements for lifts are defined in a number of national and local building codes. The American Society of Mechanical Engineers (ASME) A17.1, Safety Code for Elevators and Escalators governs elevator design and operation in all present U.S. building codes. Local Law 5 (New York 1973) is an example of a local building code. Typical requirements include an emergency recall system, proper signs, fire detectors.
linked to the recall system and special keys that can be used by fire service personnel to operate any individual car in a manual mode as long as they feel it is safe to do so.

As is the case in most countries, there currently are no national model codes that permit lifts to be used as a means of occupant egress in emergencies, and national standard ASME A17.1 (ASME 2000) requires signs at all lifts warning that they should not be used in fires. U.S. building codes (including NYC Building Code) require accessible elevators as part of a means of egress that may be used by the fire service to evacuate people with disabilities. These lifts must comply with the emergency operation requirements of ASME A17.1 (Phase II emergency operation by the fire service), be provided with emergency power, be accessible from an area of refuge or a horizontal exit (unless the building is fully sprinklered), and operate in a smoke protected hoistway. Phase II operation involves the use of a lift by a firefighter for fire service access or for rescue of people with disabilities performed under manual control (with the use of a special key).

In the event of a fire in WTC 1 or WTC 2, or other emergency requiring evacuation where the stairwells are unusable or cut off by fire and/or smoke, consideration of using lifts for occupant egress may be given in accordance with the following PANYNJ guidelines:
- Lifts may not be used if they also service the fire floor, except under specific instructions from the fire safety director or Fire Department;
- If the lifts do not service the fire floor and their shafts have no opening to the fire floor, they may be used at the direction of the fire safety director or fire department;
- Lifts under the direction of the fire department or trained building personnel may be used.

Every lift lobby contained a sign reading, “IN CASE OF FIRE USE STAIRS UNLESS OTHERWISE INSTRUCTED.” The sign also included a diagram indicating the location of the sign and the location and letter designation of each stairwell serving the particular floor.

A.2.5 Emergency communication system
WTC emergency procedures specified that all building-wide announcements were to be broadcast from the fire command station of each WTC tower, in coordination with the fire safety director or life safety and security supervisor. The deputy fire safety director was likely to make all announcements. Appendix J of the World Trade Center Emergency Guidelines provided prepared text for a variety of emergency scenarios, including power failures, fires, and service interruptions.

A.2.6 Fire command station
The fire command station, located in the lobbies of both WTC 1 and WTC 2, provided a command post for building personnel to orchestrate the response. The NYC Building Code requires that the computer screen in the fire command station monitor and display information regarding:
- Manual fire alarms
- Smoke detection
- Sprinkler water flow
- Lift lobby smoke detectors
- Fire signal activation
- Central office notification
- Fan system status
- Fail safe locked door status
- Fire system trouble
- Fire signal trouble
- Tamper switch alarm
- Power source
- Test/normal mode
- Other information as desired, including the status of lifts.

The primary value of the fire command station was its role as a convening point for key building personnel responding to a building incident. The roles of many of the key personnel are described in the next paragraph.

Figure A.8 shows the fire command station in the lobby of WTC 1 on September 11, 2001, seen from the east end of the Mezzanine Level. The fire command station appears in the back right corner of the picture.

A.3 Organisational structure

The Port Authority of New York and New Jersey (PANYNJ) produced and regularly updated an emergency procedures manual for building personnel to follow in the event of a building incident, at least until Silverstein Properties formally had become leaseholder several months prior to September 11, 2001. While Silverstein Properties was formally managing WTC 1 and WTC 2, PANYNJ staff continued to be significantly involved in property management during the transition. The latest update to the manual was completed earlier in 2001.

The fourteen chapters in the 2001 manual addressed such possibilities as bomb threats, fires, floods, gas leaks, lift emergencies, power failures, medical emergencies, chemical and fuel releases, structural integrity, and political demonstrations, among other potential problems. Aircraft impact was not specifically addressed. Individual responsibilities for key personnel were enumerated, including interactions with non-PANYNJ personnel (including, as appropriate, FDNY, NYPD, and others).

A.3.1 The Fire Safety Director

The fire safety director was a position required by Local Law 5 (New York 1973). Local Law 5 required the WTC towers to have one employee designated as fire safety director and one or more employees designated as deputy fire safety director, who possess certificates of fitness from the commissioner qualifying the individual to conduct fire drills, evacuations, and related training. A certified individual is required to be on duty during normal working hours. Consistent with Local Law 5, the primary responsibility of a fire safety director at the WTC (according to the formal emergency procedures manual) was overall emergency management for a building incident (PANYNJ 2001b). The fire safety director reports to the Fire Command Station, or scene, and assumes the following duties:

- Verify that FDNY has been notified and coordinate activities of FDNY and other emergency response personnel;
- Confer with floor wardens of affected floor(s) to determine conditions on the floor and identify areas to be evacuated, route of evacuation, stairwells available, and potential refuge floors;
- Initiate evacuation procedures;
- Direct public address announcement(s), as necessary;
- Deploy security officers to restrict access to affected and secure areas;
- Dispatch “key runs”
- Ensure appropriate notifications are initiated;
- Maintain a chronological record of the event;
- Direct the Operations Control Center (OCC) to arrange for emergency lift service;
- Investigate cause of fire (in coordination with the FDNY Bureau of Fire Investigation, prepares appropriate reports).

A.3.2 The Operations Control Center Supervisor

Upon notification of a fire event, the supervisor on duty at the Operations Control Center was to first ensure that the fire command station and the fire safety director were notified. Next, the supervisor was to issue a general broadcast of information over all WTC radio channels, monitor all channels and ensure that radio silence is observed unless directly related to the ongoing incident, arrange for lift service, update units with relevant information as necessary, and notify managers of Windows on the World (WTC 1) and Top of the World (WTC 2) of incident in order to “reduce anxiety to tenants, visitors, guests, etc. when numerous emergency vehicles respond.” The Operations Control Center was located in the B1 Level of WTC 1 and was a backup Fire Command Center.

A.3.3 The Operations and Maintenance Management team

Building operators and maintenance personnel were mobilized in order to provide emergency response assistance should the need arise. The duty supervisor established contact with the fire safety director, fire safety coordinator, or life safety and security supervisor and responded to the fire command station to assist as required. The operations group supervisor, who may have required self contained breathing apparatus, was assigned to respond to one floor below the scene of the incident, established communication with the fire command station using the floor warden telephone, assisted with the evacuation, and kept in contact with the fire command station.

The supervisor of the mechanical contractors was to dispatch staff to the fire pumps in order to “stand by” for further instructions, dispatched staff to operate the smoke purge system as requested by the fire safety director or Fire Department, and dispatched staff to secure sprinkler water shutoff valves.

The supervisor of electrical contractors was assigned to dispatch one contract electrician to one floor below the affected floor in order to assist should the incident involve electrical closets or fixtures, two electricians to the nearest sub-station below the affected floor, and a supervisor to the fire command station. Further, the electrical supervisor was to ensure that staff was standing-by in order to secure electrical power, if necessary, and that portable electrical power was available, as needed, and played a significant role in post-incident restoration of smoke detectors and/or alarm panels. In the event of a major disaster, all staff electricians were to report to the electrical shop/office.

The lift maintenance contract supervisor was to report to the fire command station in order to Figure A.9: Elevator communication panel in the fire command station of WTC 1, as operated on September 11, 2001 (NIST 2005).
assist, as needed, as well as dispatch lift mechanics to their appropriate posts to assist, as needed. Figure A.9 shows a WTC official (denoted by the vest identifying WTC Officials) attempting to communicate with lift occupants in WTC 1 on September 11, 2001, from the fire command station in the lobby.

A.3.4 The Floor Wardens

The WTC Emergency Procedures (PANYNJ 2001b) requires each floor of a high-rise building to designate a floor warden to coordinate the evacuation of the floor, consistent with NYC Building Code. Assisting the floor warden were deputy floor wardens and searchers, which constitute a tenant fire safety team. On multi-tenant floors, each tenant identified a floor warden for their space. Once the order to evacuate a floor was given, those with building authority had specific responsibilities to insure an orderly evacuation:
- In the event of an emergency, the floor warden was responsible for ensuring that an alarm was transmitted by either telephoning the police desk or activating a manual pull station. The floor warden reported the incident in detail to the Fire Command Station, and relayed instructions to building occupants.
- The floor warden was responsible for notifying occupants of the floor that there was a fire and for ensuring that the occupants executed the fire safety plan (PANYNJ 1995). In an emergency, searchers would round up employees, and the deputy fire warden would move them into the corridors and make sure all occupants were accounted for. In the event occupants were reluctant to evacuate, searchers were not required to force evacuation.
- In coordination with the Fire Safety Director, floor wardens selected the safest stairwell to use on the basis of the location of the fire, including checking the environment in the stair, and notifying the fire command station which stairwell was utilized.

A.4 Emergency response procedure

WTC policy was to conduct fire drills every 6 months, consistent with NYC Local Law 5, or shortly after move-in for all new tenants in WTC 1 and WTC 2. Written procedures specified a three-day advance notice prior to the drill for tenants, through the floor warden and deputy floor warden. The floor warden then notified all occupants of the floor.

Immediately prior to the fire drill, the public address system would be used to announce that the drill was about to occur. Occupant attendance at drills was mandatory, with a small “skeleton staff” permitted for business continuity. An occupant who missed a fire drill as “skeleton staff” was required to attend the next fire drill. The occupants were required to assemble outside a designated stairwell.

During the fire drill training, the fire alarm was sounded. The floor warden, deputy floor warden, and searchers ensured that occupants gathered in the central hallway, near a stairwell. The fire safety team then instructed the occupants not to attempt to fight fires, not to use the lifts, to obey all instructions from the deputy fire safety director, and what phone number to call if there was a problem. The location of the nearest stairwell was identified and the procedures for phased-evacuation (move three floors below the fire floor, as instructed by the floor warden and/or deputy fire safety director) (PANYNJ 1996).

The standard instruction to the occupants was to evacuate downward (to three floors below the incident floor). The training did not explicitly instruct occupants not to
evacuate upward or attempt to access the roof. Stairwells A and C went to the 110th floors, but only to serve as egress points to descend from the 110th floor or the roof. The 110th floor was not a re-entry floor, and thus, occupants without an authorized badge or a key would have been unable to reach the door that led to the roof. Had the 110<sup>th</sup> floor been accessible, actually reaching the roof would have been prevented by two additional doors, in accordance with Federal Communication Commission regulations. The first door to access the stairwell to the roof was protected by an access card reader. Upon opening the first door, the individual would enter a vestibule where, upon showing ID to a closed-circuit television monitored at the Operations Control Center (OCC), the door would be electronically unlocked from the OCC. Access to the roof was, thus, limited to a small number of people certified to enter through a radio frequency hazard awareness class.

Floor wardens, deputy floor wardens, and searchers were required as part of their training, to watch a video, prepared by PANYNJ. The video entitled “WTC Fire Safety” and provided to NIST by PANYNJ, reviewed the emergency procedures, building fire safety systems, and the responsibilities of the members of the fire safety team (PANYNJ 1996).

A.5 Account of the WTC terrorist bombing (1993)

At 12:18 p.m. on February 26, 1993, a terrorist attack resulted in an explosion in a sublevel parking garage in the World Trade Center complex, immediately killing six people (Isner and Klem 1993a; Isner and Klem 1993b) and causing an estimated $300 million damage. The explosion of at least 450 kg (1,000 lb) of explosive material caused extensive damage to several sublevels of the building and an intense fire that spread varying amounts of smoke in four of the seven buildings in the complex. Most of the complex’s estimated 150,000 occupants evacuated the buildings as a result of the incident, including approximately 50,000 from the affected towers. According to the NFPA Investigation, 1,042 people were injured in the incident, including 15 who received blast-related injuries. At the peak of the incident, the fire reached 16 alarms and involved more than 700 firefighters (approximately 45 percent of the New York City Fire Department’s on-duty personnel) (Isner and Klem 1993a). As a comparison, on September 11, 2001, 22 alarms were called prior to the collapse of WTC 2, in addition to a 10-60 alarm (unique to special operations for large incidents) and a three alarm, which staged additional units nearby. This resulted in the involvement of more than 1,000 firefighters being at the World Trade Center.

The explosion significantly damaged floors, walls, and doorways in subgrade levels and forced large amounts of smoke well away from the immediate area. In one report, visibility was reduced to 0.3 m (1 ft) within about 1 min at the 44th floor of WTC 1, largely through the spread of smoke in elevator and stairwell shafts (Isner and Klem 1993b). Before beginning evacuation, many occupants experienced smoke on occupied floors and encountered even heavier smoke as they descended the buildings in the stairwells. Since the explosion disabled the emergency communication systems in the buildings, occupants responded to the event without the planned central guidance. Even without guidance, many occupants began evacuation early in the event. Egress was further complicated by a total loss of electrical power to emergency stairwell lighting within about 1 hour and 15 min. It was estimated that it took occupants from 1½ hours to 3 hours to exit the building from the upper floors of the towers. Fortunately, the scarcity of combustibles in the subgrade levels and dilution of the fire gases limited the toxic potency of the resulting smoke. Although most of the injuries were smoke related, no
fatalities due to smoke inhalation were noted even with prolonged exposure to dense smoke.

### A.6 Account of the WTC terrorist attack (2001)

On the morning of September 11, 2001, the World Trade Center (WTC) in New York City was attacked by hijacked commercial aeroplanes. The collision with each tower (WTC 1 at 8:46:30 a.m. and WTC 2 at 9:02:59 a.m.) produced significant structural damage. The impact generated a large, luminous external fireball that consumed a portion of the jet fuel, with the remaining fuel acting as an ignition source for the combustible material within each tower. At 9:58:59 a.m., 56 minutes after it was struck, WTC 2 collapsed due to a combination of the aircraft impact damage and subsequent fire. WTC 1 stood until 10:28:22 a.m.

While most attention has properly focused on the nearly three thousand people who lost their lives at the World Trade Center (WTC) site on September 11, 2001, five times that many people successfully evacuated from the WTC towers due to heroic efforts of occupants, as well as emergency responders. Understanding why many, yet not all, survived the WTC attacks was one of the four objectives of the Federal building and fire safety investigation of the WTC disaster led by the National Institute of Standards and Technology (NIST 2005).

For the WTC towers, the times available for escape were cataclysmically established by the collapses of the buildings. Those times were not known in advance by the building occupants or the responders. The times were also considerably shorter, by a factor of three or four, than the time needed to clear the tenant spaces of WTC 1 following the 1993 bombing and an additional factor of two shorter than the time needed to clear the last person from the elevators in the building. Further, some occupants would have been unable to evacuate the buildings given any amount of time due to injuries, entrapment, and/or toxic exposure.

NIST estimates that there were 8,900 ± 750 people in WTC 1 at 8:46:30 a.m. on September 11, 2001. Similarly, NIST estimates that there were 8,540 ± 920 people inside WTC 2 at 8:46:30 a.m. New York City officially announced 2,749 fatalities at the WTC complex, including emergency responders, airplane passengers and crew (but not hijackers), and bystanders. NIST estimated that of the 17,400 ± 1,180 occupants inside WTC 1 and WTC 2 at 8:46:30 a.m., 2,146 to 2,163 perished. No information could be found for 17 persons. More than twice as many occupants were killed in WTC 1 as WTC 2, largely due to the fact that occupants in WTC 2 used the 16 minutes between the attacks on WTC 1 and WTC 2 to begin evacuating, including the use of elevators by some occupants in WTC 2.

The demographic characteristics of the evacuees was explored where the characteristics were relevant to the evacuation on September 11, 2001. Few differences
in the characteristics of WTC 1 or WTC 2 were observed. Men outnumbered women roughly two to one. The average age was mid-forties. The mean length of employment at the WTC site was almost 6 years, while the median was 2 and 3 years for WTC 1 and 2, respectively. Sixteen percent of 2001 WTC evacuees were also present during the 1993 bombing, although many other occupants were also knowledgeable about the 1993 evacuation. Two thirds of the occupants had participated in at least one fire drill during the 12 months immediately prior to September 11, 2001. Eighteen percent did not recall whether they had participated in a fire drill during that time period and 18 percent reported that they did not participate in a fire drill during that time period.

In WTC 1, all three stairwells and the elevators were destroyed in the impact region, extending as low as floor 92. No occupant evacuated from above the 91st floor, although some survived until the building collapsed after 102 minutes. Helicopter rescue from the roof was considered by an NYPD aviation unit, but deemed not possible due to the heat and smoke from the building fire. Occupants of both towers delayed initiating their evacuation after WTC 1 was hit. In WTC 1, the median time to initiate evacuation was 3 minutes for occupants from the ground floor to floor 76, and 5 minutes for occupants near the impact region (floors 77 to 91). Occupants observed various types of impact indicators throughout the building, including wall, partition, and ceiling damage and fire and smoke conditions. The most severe damage was observed near the impact region, fatally trapping some occupants. Announcements in WTC 1 were not heard by the occupants, despite repeated attempts from the lobby fire command station to order an evacuation. Damage to critical communications hardware prevented announcement transmission. Evacuation rates reached a peak, steady-state in approximately 5 minutes, and remained roughly constant until the collapse of WTC 2, when the rate in WTC 1 slowed to about one-fifth of the peak, steady-state. WTC 1 collapsed at 10:28:22 a.m., resulting in approximately 1,500 occupant deaths, 107 of which were estimated to be below the 92nd floor.

The evacuation of WTC 2 was markedly different from the evacuation of WTC 1. There was a 16 minute period after WTC 1 was attacked, but before WTC 2 was attacked. During this time period, occupants were forced to decide whether to remain inside WTC 2, and if they decided to leave, they had to choose between using one of the three stairwells or using a lift. Further complicating this decision process were multiple, conflicting announcements around 9:00 a.m., first instructing occupants to return to their offices, and then within one minute of impact, instructing them to begin an evacuation if conditions on their floor warranted that decision. Over 90 percent of WTC 2 survivors started to evacuate the building prior to its being attacked. Sixteen percent of the survivors used lifts to evacuate. Approximately 75 percent of the occupants who were above the 78th floor (the lowest floor of impact) descended to at least below the impact region prior to the attack on WTC 2. Over 40 percent of the survivors had left WTC 2 prior to 9:02:59 a.m. After WTC 2 was attacked, at least 18 individuals used Stairwell A, located in the northwest corner and furthest from the impact damage, to descend below the 78th floor to evacuate the building. Additional public address announcements were made after the airplane strike on WTC 2, although occupants who survived generally did not hear those announcements. After the initial peak in evacuation rate, the rate reached a steady-state similar to the rate observed in WTC 1 until approximately 20 minutes prior to collapse of WTC 2. The evacuation rate during the final 20 minutes dropped significantly, likely due to a decreased number of occupants remaining in the egress system below the 78th floor. NIST analysis indicated only 11 occupants initially below the 78th floor were killed when WTC 2 collapsed at 9:58:59 a.m. Overall, NIST estimated that 630 occupants of WTC 2 perished.
Constraints or aids to the evacuation progress were documented. Building announcements were cited by many in WTC 2 as a constraint to their evacuation, principally due to the 9:00 a.m. announcement instructing occupants to return to their workspaces. Crowdedness in the stairwells, firefighter counterflow, lack of instructions and information, as well as injured or disabled evacuees in the stairwells were the most frequently reported obstacles to evacuation. The most commonly mentioned forms of aid were assistance from coworkers and emergency responders and the photoluminescent markings in stairwells. Six percent of survivors in WTC 1 and WTC 2 reported a mobility impairment that slowed their evacuation. Sometimes the evacuation speed of others in the immediate area slowed down occupant evacuation speed. Recent pre-existing injuries, medications, or medical treatments were the most commonly reported mobility impairments, while a small number used wheelchairs, were pregnant, or were elderly. A rest station for mobility-impaired occupants was established in WTC 1 somewhere between floors 12 and 20. Less than 10 minutes prior to the collapse of WTC 1, the occupants and helpers on the floor were ordered to evacuate, although it remains unclear whether all rest station residents survived.

Minutes prior to the collapse of WTC 2, an NYPD Emergency Services Unit (ESU) officer radioed from a floor in the 20s to the outside that he was having trouble ascending the stairwell due to the large number of occupants descending (Interview 24 NYPD [NIST 2004]). While the origin of the occupants remains unknown, only 11 occupants who started evacuating below the impact region were known not to have survived.

A.7 Input variables for the models

For the calculation models, input values have been derived from the 2005 NIST report describing the 2001 WTC disaster.

A.7.1 General input variables

A number of general input variables are needed to calculate the egress times. The NIST 2005 report has provided the following data:

<table>
<thead>
<tr>
<th>Input variable:</th>
<th>WTC1</th>
<th>WTC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total building height (above ground level):</td>
<td>418 m</td>
<td>416 m</td>
</tr>
<tr>
<td>Total number of floors:</td>
<td>110 floors</td>
<td>110 floors</td>
</tr>
<tr>
<td>Impact region located at:</td>
<td>floor 92 and up</td>
<td>floor 78 and up</td>
</tr>
<tr>
<td>Number of usable stairwells, after impact:</td>
<td>0/3 above the impact region</td>
<td>0/3 above the impact region</td>
</tr>
<tr>
<td></td>
<td>3/3 below the impact region</td>
<td>3/3 below the impact region</td>
</tr>
<tr>
<td>Number of operational lifts, after impact:</td>
<td>0</td>
<td>1 (used by FDNY)</td>
</tr>
<tr>
<td>Average floor height:</td>
<td>3.7 m</td>
<td>3.7 m</td>
</tr>
<tr>
<td>Distance along the stair slope (including landings):</td>
<td>10 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Total width of each stairwell:</td>
<td>A: 1.1 m</td>
<td>A: 1.1 m</td>
</tr>
<tr>
<td></td>
<td>B: 1.4 m</td>
<td>B: 1.4 m</td>
</tr>
<tr>
<td></td>
<td>C: 1.1m</td>
<td>C: 1.1m</td>
</tr>
</tbody>
</table>

Table A.2: General input variables

A.7.2 Building population input variables

The building population on September 11, 2001, is not known precisely, but it has been possible to make a good estimate. The number of people in the building was limited (NIST 2005):

- On a typical Tuesday at 8:46 hours a number of the companies were not staffed yet;
The observation deck in WTC2 wasn’t open yet. September 11, 2001, was the first day of the new school year and the date of the primary election in New York City.

The estimated projection of the building population during the time of the first impact is 8900±750 individuals in WTC1 and 8540±920 in WTC2. The estimated population has also been portrayed in table A.3.

<table>
<thead>
<tr>
<th>Estimate</th>
<th>WTC 1</th>
<th>WTC 2</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated total population of survivors</td>
<td>7,470</td>
<td>7,940</td>
<td>15,410</td>
</tr>
<tr>
<td>Estimated number of occupant decedents</td>
<td>1,462 – 1,533</td>
<td>630 – 701</td>
<td>2,146 – 2,163</td>
</tr>
<tr>
<td>Estimated decedents above impact zone</td>
<td>1355</td>
<td>619</td>
<td>1874</td>
</tr>
<tr>
<td>Estimated decedents below impact zone</td>
<td>107</td>
<td>11</td>
<td>118</td>
</tr>
<tr>
<td>Estimated total building population</td>
<td>8,960</td>
<td>8,600</td>
<td>17,560</td>
</tr>
</tbody>
</table>

Table A.3: Occupancy estimates on September 11, 2001, by tower (NIST 2005)

A.7.3 Lift input variables of WTC1 and WTC2:
The manner in which the lifts in the WTC towers have been zoned is crucial to know as well. The following tables will describe the building zones, local lift groups, number of local lifts, shuttle lifts etc.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Floor(s)</th>
<th>WTC1</th>
<th>WTC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9 – 40</td>
<td>Tenant space</td>
<td>Tenant space</td>
</tr>
<tr>
<td>7, 8</td>
<td>Mechanical floors</td>
<td>Mechanical floors</td>
<td></td>
</tr>
<tr>
<td>Exit</td>
<td></td>
<td>Concourse level</td>
<td>Discharge level</td>
</tr>
<tr>
<td>2</td>
<td>45 – 74</td>
<td>Tenant space</td>
<td>Tenant space</td>
</tr>
<tr>
<td>75, 76</td>
<td>Mechanical equipment</td>
<td>Mechanical equipment</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>79 – 106</td>
<td>Tenant space</td>
<td>Tenant space</td>
</tr>
<tr>
<td>107</td>
<td>Windows on the World</td>
<td>Indoor observation deck</td>
<td></td>
</tr>
<tr>
<td>108 – 110</td>
<td>Mechanical equipment</td>
<td>Mechanical equipment</td>
<td></td>
</tr>
</tbody>
</table>

Table A.4: grouping the WTC towers into zones.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Floor(s)</th>
<th># of lifts, lift type</th>
</tr>
</thead>
<tbody>
<tr>
<td>(top)</td>
<td>107</td>
<td>2 shuttle lifts</td>
</tr>
<tr>
<td>3</td>
<td>80 – 106 (27 floors)</td>
<td>24 local lifts (4 groups)</td>
</tr>
<tr>
<td>78</td>
<td>8 shuttle lifts</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>46 – 74 (29 floors)</td>
<td>24 local lifts (4 groups)</td>
</tr>
<tr>
<td>44</td>
<td>8 shuttle lifts</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>9 – 40 (32 floors)</td>
<td>24 local lifts (4 groups)</td>
</tr>
<tr>
<td>Exit</td>
<td></td>
<td>Concourse level</td>
</tr>
</tbody>
</table>

Table A.5: WTC lifts and lift groups

Table A.1 in paragraph A.1 listed the different floors of towers WTC1 and WTC2. These floors have been grouped in table A.4 in order to simplify the location of the zones within the building and identify them more clearly. These zones have been condensed further in table A.5.

In order to add the theoretical possibility of using lifts to evacuate (particularly for WTC2), the lift system parameters have been added. The following data has been derived from a publication by J.W. Fortune (1998): each of the skylobbies was serviced by 8 shuttle lifts. Each lift had a max. load of 4500kg or 50 persons (thus assuming each person weighs 90kg), and a nominal load of 30-35 persons. The net platform area of a lift car was 7,8m². The lift speed of the shuttles was 8,0 m/s.
Note that the 24 local lifts did not service all local floors, as can be seen in figure A.11: 4 groups of 6 lifts serviced a part of the local zones. One could reason that 3 out of 4 lift groups could be used for evacuation type 3a (with alterations in building design to accommodate an extra (emergency) landing floor for the higher lift group shafts).
Alternatively, one could design an emergency landing floor at the top levels of group 1 and 3: all 24 lifts could then be used for an evacuation scenario 3b.

Barney (2002) provides the following information regarding the local lift groups:

Stack 1 had 4 groups of 6 single deck lifts serving:
Main Terminal and Floors 9-16 at 4 m/s;
Main Terminal and Floors 17-24 at 5 m/s;
Main Terminal and Floors 25-32 at 6 m/s; and
Main Terminal and Floors 33-40 at 7 m/s.

Stack 2: from the sky lobby (floor 44) there were 4 groups of 6 single deck lifts serving:
44 and Floors 46-54 at 2.5 m/s;
44 and Floors 55-61 at 4 m/s;
44 and Floors 62-67 at 4 m/s; and
44 and Floors 68-74 at 5 m/s.

Stack 3: from the sky lobby (floor 78) there were 4 groups of 6 single deck lifts serving:
78 and Floors 80-86 at 2.5 m/s;
78 and Floors 87-93 at 4 m/s;
78 and Floors 94-99 at 4 m/s;
78 and Floors 100-106 at 5 m/s.

In addition there were a group of 3 single deck interzone shuttles between Floors 44 and 78 at 8 m/s. In addition to the local and shuttle lifts there were 7 freight lifts. 1 freight lift had access to all floors (the rest serviced local zones).

Regrouping the data of the local lift groups to fit scenarios 3a and 3b gives the following estimates:

<table>
<thead>
<tr>
<th>Stack 1</th>
<th>Stack 2</th>
<th>Stack 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of discharge level:</td>
<td>Concourse (Floor 0)</td>
<td>Skylobby floor 44</td>
</tr>
<tr>
<td>Local lift group zones:</td>
<td>Floor 9 - 40</td>
<td>Floor 46 - 74</td>
</tr>
<tr>
<td>Scenario 3a:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floors bottom zone – top zone:</td>
<td>9-23= 15</td>
<td>24-40= 17</td>
</tr>
<tr>
<td>Rendez-vous level at:</td>
<td>Floor 24</td>
<td>Floor 61</td>
</tr>
<tr>
<td>Number of lifts available at rendez-vous level:</td>
<td>18 lifts</td>
<td>18 lifts</td>
</tr>
<tr>
<td>Average lift speed:</td>
<td>6 m/s</td>
<td>4.3 m/s</td>
</tr>
<tr>
<td>Scenario 3b:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>Rendez-vous levels at:</td>
<td>Floor 16</td>
<td>Floor 29</td>
</tr>
<tr>
<td>Number of lifts available at rendez-vous levels:</td>
<td>12 lifts</td>
<td>12 lifts</td>
</tr>
<tr>
<td>Average lift speed:</td>
<td>4.5 m/s</td>
<td>6.5 m/s</td>
</tr>
</tbody>
</table>

Table A.6: WTC lift design parameters used for calculation scenarios 3a and 3b.
Table A.6 shows that the rendez-vous levels / transition floors depend on the reach of the local lift shafts. In scenario 3a only 18 out of 24 lifts can be used, simply because at half the height of the local zone (floors 24, 61 and 93) the lowest group of 6 lifts isn’t available at this height. In scenario 3b, the first rendez-vous level is determined by the highest landing floor of the lowest lift group (floors 16, 54 and 86). The second rendez-vous level can be manipulated to make the top two zones as equal as possible, in order to distribute the population evenly among the two rendez-vous levels. Note that at these floors the higher of the two lift groups will need “emergency” landing doors built into the lift shaft in order to allow access for emergency egress (in the “standard” situation, a higher lift group doesn’t have landing doors in the (lower) zones that they do not service).

A.8 Data provided by the WTC attack 2001

The data regarding the pedestrian egress during the 2001 WTC disaster has been recorded in detail. The following data can be used for comparison with the model calculation results.

A.8.1 Pedestrian speed

WTC 2001, North Tower yielded the following results:
Mean normalized travel speed: 1.3 floors per minute; distance along the stair slope (including landings): 10m. => Movement speed in the stairwells: 0,2 m/s
This low speed was due to crowding and obstacles (NIST 2005). NIST concluded that the actual pedestrian flow was 1,5 people per second, or 0,5 people per second per door. This is about half the flow rate when calculated according to the method used by Fruin (1987).

A.8.2 Decrease of the building occupancy over time

The NIST report (2005) provides a detailed graph that clearly shows how the rate of egress in towers WTC1 and WTC2 progressed over time. Data visualised in this form is very rare and can provide much insight about the development of the emergency egress process over time and the possible constraints in this process.

Figure A.12: Percentage of occupants remaining in the building for WTC1 and WTC2 (NIST 2005)
Table A.6 has been derived from figure A.12 and provides an overview of the percentage of occupants remaining in the building for WTC1 and WTC2:

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>WTC1</th>
<th>WTC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>5</td>
<td>95</td>
<td>96</td>
</tr>
<tr>
<td>10</td>
<td>92</td>
<td>84</td>
</tr>
<tr>
<td>15</td>
<td>89</td>
<td>83</td>
</tr>
<tr>
<td>20</td>
<td>83</td>
<td>77</td>
</tr>
<tr>
<td>25</td>
<td>59</td>
<td>72</td>
</tr>
<tr>
<td>30</td>
<td>53</td>
<td>64</td>
</tr>
<tr>
<td>35</td>
<td>42</td>
<td>59</td>
</tr>
<tr>
<td>40</td>
<td>38</td>
<td>43</td>
</tr>
<tr>
<td>45</td>
<td>34</td>
<td>37</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td>55</td>
<td>27</td>
<td>25</td>
</tr>
<tr>
<td>60</td>
<td>23</td>
<td>18</td>
</tr>
<tr>
<td>65</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>70</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>75</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>80</td>
<td>18</td>
<td>-</td>
</tr>
<tr>
<td>85</td>
<td>17</td>
<td>-</td>
</tr>
<tr>
<td>90</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>95</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td>105</td>
<td>13</td>
<td>-</td>
</tr>
</tbody>
</table>

Table A.6: Percentage of occupants remaining in the building for WTC1 and WTC2 (5-minute intervals, NIST 2005)

An important note is that the 2005 NIST report declared that the egress flow rate decreased through time due to the fact that a separation had occurred between the ‘faster’ and the ‘slower’ building occupants, leaving primarily the ‘slower’ building occupants inside the buildings: stating that the observed curves were caused by fatigue would therefore be too simplistic. In addition, the egress flow rate in WTC1 dropped dramatically after the collapse of WTC2, which caused the conditions in which the WTC1 occupants had to move through, to deteriorate (NIST 2005).

A.8.3 Evacuation delay times in WTC1 and WTC2

Another important note is the importance of evacuation delay times. Both curves appear to resemble “S-curves”, illustrating how the egress flow rate needed to get started in the beginning. This remark can be viewed as “stating the obvious”, but when comparing the data to calculated models, proper attention needs to be given to incorporate evacuation delay times. Table A.7 and A.8 show the evacuation delay times for WTC1 and WTC2.

### Table A.7: Elapsed time (min) to initiate evacuation for survivors from WTC1 (NIST 2005).

<table>
<thead>
<tr>
<th>Time for Survivors to Initiate Evacuation*</th>
<th>25% Initiation</th>
<th>50% Initiation</th>
<th>75% Initiation</th>
<th>Mode of Responses</th>
<th>Average Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower floors (Basement – 42)</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>5.7</td>
</tr>
<tr>
<td>Middle floors (43–76)</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>4.8</td>
</tr>
<tr>
<td>Upper floors (77–91)</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>1</td>
<td>7.4</td>
</tr>
</tbody>
</table>

* Time to begin evacuation is the time interval from first awareness to the time the respondents left their floor to begin evacuation.

Source: NIST WTC Telephone Survey Data.

### Table A.8: Elapsed time (min) to initiate evacuation for survivors from WTC2 (NIST 2005).

<table>
<thead>
<tr>
<th>Time for Survivors to Enter Stairwell†</th>
<th>25% Initiation</th>
<th>50% Initiation</th>
<th>75% Initiation</th>
<th>Mode of Responses</th>
<th>Average Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower floors (Basement – 42)</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td>6.3</td>
</tr>
<tr>
<td>Middle floors (43–76)</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>7.1</td>
</tr>
<tr>
<td>Upper floors (77–110)</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>4.2†</td>
</tr>
<tr>
<td>Upper floors (77–91)</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>7.1</td>
</tr>
</tbody>
</table>

† Time to begin evacuation is the time interval from first awareness to the time the respondents left their floor to begin evacuation.

b. The evacuation delay results may contain significant bias for the upper floors in WTC 2, as discussed in the text.

Source: NIST WTC Telephone Survey Data.

NIST (2005) adds the following remark regarding table A.8: “the evacuation delay results may be biased for the upper floors in WTC 2, however, as only occupants who acted quickly to move below the 78th floor before 9:02:59 a.m. could be interviewed. In other words, those who delayed for whatever reason, with few exceptions, did not survive. The impact of this potential bias was not quantified, but should be noted.”

Based on the average delay times shown in table A.8, one could assume a delay time of around 5 minutes when adding the calculation results in comparison to the observed data from September 11, 2001.
A.8.4 Correctional factors for the egress flows in WTC 1 and WTC2

Before the data can be used for comparison, a few important questions must be answered. For one the fact that (practically) nobody above the impact zones had access to an accessible stairwell after impact, means that any calculations including these upper floors would produce incorrect results. In addition the use of lifts in WTC2 during the crucial 16 minutes before impact is cause for biased results: Figure A.12 shows the relatively high amount of evacuees leaving WTC2 per minute, compared to WTC1.

The 8960 occupants in WTC1 and the 8600 occupants in WTC2 are assumed to be situated in zones 1 (floors 9-40: 32 floors), 2 (floors 45-74: 29 floors) and 3 (floors 79-106: 28 floors). The total of 89 floors would suggest an occupancy level of 100,67 persons/floor in WTC1 and 96,62 persons/floor in WTC2.

- WTC1: Impact at floor 92+; 106-92=14 floors, which would translate to:
  14*100,67=1409 people above the impact region.
  The NIST report documented 1355 people who perished above the impact zone and an additional 107 civilian deaths below the impact zone. In this case the assumed population spread seems to work reasonably well (margin of error is about 50 people).

  1355 out of 8960 people translates to 15,1% in the top 14 floors. For a modified egress calculation one could assume 84,9% or 7605 people in the 89-14=75 remaining tenant floors, making the occupancy level 101,4 people per floor and making the top floor 110-91=19 floors lower: with a floor height of 3,7m the ‘functional’ building height in WTC1 would become 418-(3,7*19)= 347,7 meters.

- WTC2: Impact at floor 78+; zone 3 = 28 floors, which would translate to:
  28*96,62= 2705 people above the impact region (if there hadn’t been a 16-minute delay (!)).
  The NIST report documented 619 people who perished above the impact zone and an additional 11 civilian deaths below the impact zone. In this case the assumed population spread is difficult to verify, since the egress flow during the first 16 minutes before the second impact was influenced a great deal because of the use of lifts during that time frame.

  During the first 16 minutes WTC2’s entire building height is applicable, although the data is biased because of the use of the lifts, as stated before. A second calculation can be attempted at 16 minutes however: at 16 minutes about 68% of the total building population was still inside (5848 of the 8600 occupants). 619 people were above the impact zone (=7,20%). At 16 minutes WTC2’s functional height became 110-78=32 floors shorter, i.e. the functional building height became 416-(3,7*32)= 297,6 meters. A simplified model would yield 5848-619= 5229 occupants: when divided in low and mid tenant zones (32+29=61 floors), one would get a modified occupancy level of 85,72 people/floor.
A.9 Comparing building evacuation times: recorded data versus models

After having given some background information about the building, its features and the procedures, a comparison is given between the data that is available via the investigation report of the 2001 disaster and the evacuation times predicted by the models described in this thesis.

A.9.1 Comparing the total pedestrian egress times

The remaining occupants as shown in figure A.11 can be predicted by entering the input values into the calculation models. The results can provide an answer to one of the main questions of this thesis: which method is more accurate, the traditional method or the method with the proposed additional factors?

Plotting the calculated egress curve (for both the traditional method and the added factors) together with the observed curve yields the following results:

Figure A.13a (top): The compared occupancy egress progressions for tower WTC1. Figure A.13b (bottom): The compared egress progressions with an added 5-minute delay and without the risk blockage factor.
The curves in figure A.13 show the comparative egress progressions for tower WTC1. The top curve clearly shows that the traditional method is much too optimistic, but also that the chosen factors slow down the expected pedestrian speeds too much. In addition, the curve displaying the observed egress progression in WTC1 at 9/11 has the form of an "S-curve", showing the influence of the delay time prior to evacuation.

With these observations in mind, two alterations were made to form the bottom curve. The first alteration was to add a 5-minute evacuation delay for the calculated curves, based on the data in paragraph A.8.3. The second alteration was to scrap the risk blockage factor: with the demographic factor and risk factor both set to 1, only the fatigue factor influenced the new calculations.

With these alterations the curve with fatigue factor appears to follow the WTC curve reasonably well; at 75 minutes the WTC curve bottoms out, but when reminded that the egress speed dropped from this moment on due to the collapse of WTC2, this difference can be explained. The difference between the calculated and measured egress times are reasonably small. One can conclude that, with better calculation factors, this calculation method may prove to yield useful results. Figure A.14 shows the comparative results for WTC2:

Figure A.14a (top): The compared occupancy egress progressions for tower WTC2. Figure A.14b (bottom): The compared egress progressions with an added 5-minute delay and without the risk blockage factor.
In Figure A.14a the traditional curve more or less follows the WTC2 curve quite well up to about 35 minutes, whereas the curve with the additional factors displays a very low egress speed in comparison. As mentioned however, the WTC2 data has been ‘contaminated’ by the use of lifts during the 16 minutes prior to the impact of the second airplane: the slope of the WTC2 curve is therefore relatively steep.

After adding the same alterations as in the graph for WTC1 (adding a 5-minute delay and disregarding the blockage risk factor), the relatively steep angle of the WTC2 curve becomes more visible. The traditional method seems to provide a more accurate prediction, although at around 78 minutes the factored curve crosses paths again with the WTC2 curve. Altogether it is rather difficult to draw any clear conclusions from this set of data.

One possibility would be to reset the calculations to 16 minutes, when tower 2 is hit. From this moment in time the occupants only have use of the stairs. As the evacuation is already in progress, no delay times should be added to the calculated curves. The factored curve should utilise the estimated fatigue factor at 16 minutes though, as the evacuees should theoretically already feel the effects of their journey so far. These new input values give the following results:

In figure A.15 the traditional curve soon becomes too steep, suggesting that the egress flow in the stairwells does indeed slow down. The calculations with the fatigue factor (no blockage risk factor) still produce a curve that displays a slower egress speed, but for a while it does run parallel to the WTC2 curve. Still the conclusion must be however that neither curve can replicate the way in which the egress speed in tower 2 progressed.

A.9.2 Evacuating the WTC towers via lifts: scenarios 3a and 3b + shuttle lifts

While the lifts were knocked out from the start in WTC1, WTC2 still had use of its lifts for 16 minutes. The NIST report (2005) states literally that the use of the lifts in WTC2 during those 16 minutes saved many lives: the question arises if even more people could have been saved if there had been an evacuation plan using the lifts.

In order to answer this question, a fictitious evacuation has been calculated for the scenarios 3a and 3b (these have proven to yield the fastest egress times in chapter 11). In addition the times were calculated in which the shuttle lifts could transport the
evacuees from the skylobbies down to the Concourse level. The calculation results have been summarized in table A.9:

<table>
<thead>
<tr>
<th>Input variable:</th>
<th>WTC1 (low zone)</th>
<th>WTC1 (mid zone)</th>
<th>WTC1 (top zone)</th>
<th>WTC2 (low zone)</th>
<th>WTC2 (mid zone)</th>
<th>WTC2 (top zone)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of floors (total):</td>
<td>43 (0-43)</td>
<td>34 (44-77)</td>
<td>29 (78-106)</td>
<td>43 (0-43)</td>
<td>34 (44-77)</td>
<td>29 (78-106)</td>
</tr>
<tr>
<td>Number of tenant floors:</td>
<td>32</td>
<td>29</td>
<td>28</td>
<td>32</td>
<td>29</td>
<td>28</td>
</tr>
<tr>
<td>Population of the zone:</td>
<td>3222</td>
<td>2920</td>
<td>2819</td>
<td>3092</td>
<td>2802</td>
<td>2706</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3a, stairs):</td>
<td>9/11 min</td>
<td>9/9 min</td>
<td>8/8 min</td>
<td>9/9 min</td>
<td>8/8 min</td>
<td>8/8 min</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3a, lifts):</td>
<td>-</td>
<td>24 min</td>
<td>29 min</td>
<td>-</td>
<td>24 min</td>
<td>29 min</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3b, stairs):</td>
<td>8/8 min</td>
<td>7/7 min</td>
<td>7/7 min</td>
<td>6/6 min</td>
<td>6/6 min</td>
<td>6/6 min</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3b, lifts):</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table A.9 shows that the handling capacity of the shuttle lifts proves to be the bottleneck: this observation has been made as well in chapter 11 and in Appendix C. The calculations show that the zones in-between the skylobbies are empty within 11 minutes (maximum), after which the stairwells would have been empty and the building occupants would have been concentrated in the skylobbies at floors 44 and 78.

When regarding WTC tower 2 in 2001, the calculations suggest that the 619 people who died above the impact zone would still have been alive if an evacuation system like scenario 3a or 3b had been applied for the Twin Towers. Furthermore, congestion in the stairwells would have dissolved within a maximum of 11 minutes, freeing them up for the emergency rescue services. The skylobbies could be designed as refuge areas and even become secondary Fire Command Stations, from where the emergency services can co-ordinate their actions and tend to the evacuees while they are waiting to be shuttled down. These two observations (all building occupants accumulated in two secure areas (skylobbies) and all stairwells empty in ten minutes) are compelling arguments in favour of integrating lifts into the evacuation protocols.

However: making conclusions in hindsight should be done with caution, as every incident is different and any statements applying to one situation would be useless in a different incident. This can be demonstrated by the following observation: the impact zone where the second airliner (United Airlines Flight 175) hit WTC2, ranged from floor 78 (!) to floor 84. 12 out of 18 survivors from floor 78 and up were located on the 78th floor at the time of impact, of which one died several days later as a result of his/her injuries. This means that, had the aircraft hit the building just a few meters lower, most if not all occupants in the skylobby would have been killed. When translating this back to the evacuation scenario 3a/3b, 16/29 or 55% of the top building zone would have been shuttled down at the time of impact. 45% of that zone would have perished while waiting for the shuttle lifts, which amounts to (45% * 2706 = ) 1213 casualties. In other words: 594 more people would have been killed in this hypothetical situation.

### A.10 Conclusions and debate

The 9/11 World Trade Center disaster is a compelling example of the duality of the answer to the question: "Is it beneficial to use lifts for emergency egress in tall buildings?". The calculations show that using lifts for emergency egress would shorten evacuation times significantly. The rendez-vous levels and skylobbies form natural focal points for the building officials when providing information and sending personnel to direct the evacuation process.
The flip side is that the lifts need to be functional in order for the system to work, and that the evacuation process may not dissolve into chaos if, by remote chance, the lifts do not function (i.e. backup procedures are necessary).

In the end the answer is about the level of safety that should be required by society. No building can be completely protected from extraordinary events like a terrorist attack of this magnitude. A terrorist will always target the weak spots of a building, and there will always be a chance that a severe earthquake occurs in an otherwise seismic ‘quiet’ area like the Netherlands. With this in mind, the benefits of using lifts for emergency egress outweigh the risks.

The advised evacuation protocol for the WTC towers would have been to assign local rendez-vous levels, use the local lift systems as described in scenario 3a/3b and design the two skylobbies as temporary refuge areas, where building occupants can talk among each other, gather information from emergency response personnel and receive treatment while waiting for their turn to be transported to the exit level via the shuttle lifts. In addition, each local lift group would have one lift that could serve all floors: one ASS team (Appointed Safety Supervisors) would be assigned to this lift to pick up any building occupants unable to use the stairs.
Appendix B

Test case 2; Delftse Poort, Rotterdam
B TEST CASE 2; DELFTSE POORT, ROTTERDAM

The second test case is the Delftse Poort, an office building in Rotterdam. Until 2005 this building used to be the highest office building in the Netherlands. The Delftse Poort was built in 1991, has 41 stories and is 151 meters high (www.skyscraper.city.info). From an international perspective, this height is unremarkable. The number of buildings in the Netherlands that equal or exceed this height is increasing however: the Maastoren in Rotterdam will stand at a height of 165 meters on completion, and plans have been made to construct the Belle van Zuylen tower in Utrecht. If the latter is realised (planned to be in 2014), this new tower will be 262 meters high. In any case, the Delftse Poort presents a good representation of a Dutch office building, and is a good case study to illustrate the Dutch building environment.

B.1 General information

The Delftse Poort, designed by the architect A. Bonnema, was built in 1991 (Mens 1996). The complex consists of two towers, conjoined at the bottom by a low-rise section. The first tower is 151 meters high and counts 42 floors (including the ground floor). The second tower is 93 meters high and counts 26 floors. The entire complex was designed to house 3000 employees of the Dutch insurance firm Nationale Nederlanden, which is owned by the ING Group. The complex currently houses approximately 4000 employees. The total square footage is 106,000 m² (including a restaurant and spacious conference areas), and the net office space is 66,000 m².

The generous assistance provided by ING Facility management ops / Security liaison of the building, mister Huib van der Sluis, yielded a lot of valuable information, communication (both via email and face-to-face) and feedback regarding emergency response, evacuation drills, protocols and organisation. The evacuation drills for the Delftse Poort provide useful data within the context of the Dutch building industry. It therefore can serve as a test case to determine if buildings in the 70-250 meters range can benefit from the integration of lifts into the evacuation process.

A vertical cross-section of the complex shows the following layout, see figure (B.2). The Delftse Poort (or “DP”) is divided into four sections. DP0 is the low-rise section, going from the parking level at level –1 to the plaza at +3 that connects the three sections above it. Sections DP1 and DP2 are the towers; DP3 is a lower, central section between these two towers.

Section DP0 is the large low-rise section that connects the three towers above it. It has one parking deck below ground level and two other parking decks at the second and third floor (hereafter referred to as levels 1 and 2). The ground level (in the Netherlands the ground level or first floor is referred to as “floor zero”) has been reserved for a large entrance lobby, with vides reaching up to the third level. It also contains loading bays for deliveries and the security centre, which doubles as the Incident Command Post (ICP).
A number of escalators and glass lifts provide access to level 3, which serves as an indoor plaza where employees can meet up and access the main elevator lobbies to the three sections above.

Section DP1 is the highest tower (151 meters). Levels 4, 5 and 40 are non-public floors for building installations, level 39 is an archive area and levels 6 to 38 are reserved for ‘regular’ office space. The tower itself has been divided into a low-rise, ‘double’ section with workspaces for 105 employees per floor, and a high-rise, ‘single’ section with 55 employees per floor. There are two elevator groups: one for the low-rise section (level 6 – 18) and one for the high-rise section (level 19 – 38). The high-rise group contains two fire-fighter’s lifts that have stops at all floors, including the low-rise section. The top two floors are serviced by a single hydraulic lift (level 38 – 40).

Tower DP2, with a total height of 103 meters, is not as high as DP1. Like DP1, it has a ‘double’ section for 105 employees per floor (level 6 – 11) and a ‘single’ section for 55 employees per floor (level 12 – 22). In contrast to DP1 however, only one lift group serves the second tower. DP2 also has an archive and a technical floor at the top, and two of the lifts in the group are fire-fighter’s lifts.

B.2 Building safety features

In case of an emergency, the Delftse Poort has an impressive array of safety features. Compared to the Dutch Building Code, these features are far superior to the minimum requirements. The reason for this is that in its time, the height of this building was unprecedented in the Netherlands. As explained in paragraph 4.1, the Dutch Building Code was (and still is) technically only valid for buildings below 70 meters; above that, building designers and city officials need to determine what an acceptable, "equality-based" solution is. When raising the standards to (literally) new heights, the Dutch parties involved in the designing and building wanted to ensure that the building’s performance during an emergency situation would prove to be excellent. One important
reason for this was that Nationale Nederlanden is an insurance company; therefore they were prepared to spend more money to acquire a solid, safe, dependable building that matched their image.

**B.2.1 Active and passive features**

First of all, all floors are protected by both active means (sprinkler system) and passive means (compartmentalisation). The Dutch building code officially only requires passive protection or, based on the ‘equality principle’, a sprinkler system. This implies that where WTC 7 in New York was subject to progressive collapse because the water mains had been destroyed (NIST 2008), the open space in the Delftse Poort has been limited to such an extent that progressive collapse should not occur, even if the sprinkler system fails.

The building’s emergency power grid is a noteworthy feature as well. An emergency generator can provide 2,450 kVA if the regular power grid fails, and a second loop in the main wiring offers redundancy that can be used to re-route the electric current if the primary grid is damaged.

**B.2.2 Evacuation via stairs and lifts**

As can be seen in figures (B.1) and (B.2), one of the building’s defining features is that the transition from the low-rise zone to the high-rise zone can *literally* be seen from outside the building. The low-rise zone (105 work spaces) consists of two wings that are slightly askew from each other; one of these wings stops at the high-rise zone, giving the towers their stepped silhouette.

This design defines the way in which elements like the building cores and the emergency stairwells have been placed. Both towers (DP1 and DP2) have one central core in the conjoined low-rise / high-rise area, where it forms the centre of the tower; when the high-rise section starts, this core forms one side of the building section, as if only one of the two ‘wings’ is left. The highest tower (DP1) has two separate lift groups in two separate lobbies: the low-rise lifts are situated in one side of the core and the other side of the core houses (among others) the high-rise lifts.

Figure (B.3) shows the building during its construction phase: it shows quite clearly how the cores are situated in respect to the rest of the building structures. In addition one can see where in tower DP1 (the tower to the right) the lift shaft for the low-rise group ends: above the height of the two grey cranes (just above the low-rise section, which already has most of its façade completed), the space is used for additional office space.

The low-rise zones of both buildings each have 3 emergency stairwells: one at the building core and one at the ends of each wing. When the low-rise zone ends, 2 emergency stairwells remain: the one at the core and the other at the opposite end of the high-rise wing. The pressurized emergency stairwells provide protection against smoke. At every floor, these stairwells are separated from the rest of the floor by two
fire- and smoke-resistant doors (30 mins.) as required by the building code. In addition these stairwells are segmented for better compartmentalisation and to limit the capacities of the respective pressurization systems.

Finally, two of the lifts in the lobby serve a dual function as freight lift and reserve fire-fighter’s lift (one fire-fighter’s lift for tower DP2). An intense communication and coordination with the fire department of Rotterdam has made it possible that the ASS team is allowed to evacuate the people who cannot use the stairs via these lifts. The lift lobby is located between the two fire-resistant doors leading to the emergency stairwell, which means that the stairwell remains accessible from the lift lobby for at least 30 minutes. In addition, the lift lobby itself can be sealed off by a fire- and smoke-resistant door, protecting the lobby for an additional 60 minutes. The lobby has been equipped with enhanced fire/smoke detectors.

The security monitoring area at ground level doubles as an Incident Command Post (ICP), where every alarm of any kind is displayed on a large vertical cross-section of the building via LED lights. The bottom four floors of the low-rise section have been added as horizontal cross-sections, due to their increased size and complexity. Here, the designed system actually includes a number of switches to allow the normal lifts to be switched to evacuation mode (!). Although this feature is technically available, the ASS team and the fire department of Rotterdam have agreed to not use this feature, but to use the stairwells for emergency egress.
Another example that illustrates the excellent standard of safety measures is the organisational structure of the in-house emergency response team. An overview of this structure has been provided in figure (B.6). The organisation has been divided into three groups: each group has a leader/coordinator, who in turn report to the head of the team of Appointed Safety Supervisors (ASS), in this case mister Huib van der Sluis.

The first group is the company fire brigade. This group of volunteer fire-fighters has the training, the equipment and the authority to investigate an alarm, rescue any endangered people and attack the fire. They also assume the role as guides, once the city fire department arrives. In addition, they can be called on to assist in the evacuation of disabled people.

The second group is the first aid team: these people have the task of providing first aid where necessary. Besides providing first aid upon request (via a page) where needed, they also maintain a permanent presence at the Incident Command Post (ICP) at ground level. They too can be called upon to assist in the evacuation effort.

The third and largest group (200+ people) are the Appointed Safety Supervisors (ASS). While the first two groups gather at the ICP, the main body of the ASS team is divided over the floors of the building. Each floor has one floor warden who acts as the supervisor for the ASS team of that floor. The team is responsible to prevent panic, gather the employees of ‘their’ floor and direct them towards the emergency exits. The employees unable to use the stairs are directed to the lift lobby, where these employees are accompanied while waiting for evacuation via the fire-fighter’s lifts. They also sweep the floor for any stragglers before declaring the floor “evacuated”.

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**Figure B.6: Organisational structure of the Safety Management Team of the Delftse Poort.**

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It is important to emphasise that this level of organisation is exceptional in the Netherlands: the Delftse Poort is one of the handful of companies to have an in-house fire brigade. It is a testimony of the cautious nature of the Dutch building industry and the way in which it responded to the aspiration to build an exceptionally tall building, at least in regard to the Dutch standards of almost two decades ago.

**B.4 Emergency response procedure**

When an emergency situation occurs, there are a number of alarm signals that follow:
1. The rally signal
2. The pre-alarm
3. The main alarm (or slow-whoop)
4. The signal indicating that the building is safe again.

If a smoke/fire detector is triggered or in other situations where evacuation is required, the above procedure will be utilised. If a sprinkler head is activated however or if the fire alarm is activated manually, the procedure is different for the area under immediate threat. On the incident floor, together with the floor above and below it, the main alarm (slow-whoop) is sounded immediately, skipping the first two alarms. The rest of the building occupants follow the standard procedure.

**B.4.1 The pre-evacuation stage**

The standard procedure starts with the pre-alarm, a spoken text announcing the intended evacuation to all building occupants via the intercom. It is immediately followed by the second signal: the rally signal. The rally signal are ten short beeps sounded via the intercom throughout the entire building. Although everybody can hear the signal, it is meant for the ASS team only. All ASS’s are required to head straight to the lift lobby, where the floor warden can confirm how many ASS personnel he has at his disposal. Instructions are given and preparations are made like donning brightly coloured armbands to make themselves recognisable. All necessary equipment is present in a cabinet in the lift lobby. Everything is done according to the step-by-step procedure cards. If there is no floor warden, the ASS team members assign among themselves a floor warden for their floor.

When ready, the ASS team direct all the occupants of that floor towards the fire- and smoke protected hallway and lift lobby in front of the emergency stairwells. The occupants that cannot use the stairs are grouped in the lift lobby, together with at least one Appointed Safety Supervisor. Note that nobody is allowed to enter the emergency stairwell yet.

**B.4.2 Evacuation stage**

The third signal is sounded three minutes after the rally signal. It is the main evacuation alarm: the sound of this alarm is the commonly known “slow whoop”. Upon this signal the building occupants of that floor enter the emergency stairwell and head down towards safety. Once at the ground floor, they are directed towards the general rally point outside the building.

The ASS team sweeps the entire floor, looking for stragglers. Once the floor is empty, they close the fire- and smoke resistant door and hang a “droplet” on the door handle to indicate that that floor has been pronounced “evacuated” and to serve as an extra warning not to enter that floor (see figure B.8). The floor warden is the last person to head down the emergency stairwell: he uses the evacuation procedure card to report to the ICP and sign off.
Note that simple tools like the evacuation procedure card, an armband or the “water droplet” can be very effective: especially during emergencies, simple is most often best.

The floor warden is responsible for alerting the ICP of the presence of the number of disabled occupants left in the lift lobby as soon as possible, either via the emergency phone system or in person. There is no discussion about who is able to use the stairs or not: all people claiming to be unable to use the stairs are collected in the lift lobby to avoid unnecessary debate. Together with at least one ASS, they wait near the two fire-fighter lifts until it is their turn to be taken down.

If necessary, disabled occupants can be evacuated via the stairs using the available “EVAC Chairs” or the stretchers.

**B.4.3 Organisational aspects of the emergency response procedure**

In order to reduce congestion and make the emergency egress via the stairs less claustrophobic, the building has been divided in groups of five floors. First the main alarm (slow-whoop) is sounded for the bottom five floors. One minute later, the slow-whoop is sounded in floors six to ten. One minute after that, the third group of five floors is given the main signal, and so forth. This creates some room inside the emergency stairwell, allowing the building occupants to spread out a bit, dependant on their individual preferences.

The evacuation of the disabled occupants via the fire-fighter’s lifts is executed top-down. Using the control override key, the assigned lift operators head to the top floor first. From there, the two lifts work their way down to evacuate those waiting in the lift lobbies.

The members of the in-house fire brigade and the first aid team all have pagers to ensure a quick response. Both teams head first to the ICP, where they receive information and instructions from their team leaders. Dependant on the information received from sources like the detectors and the emergency phone lines, teams are formed and dispatched to the location(s) where they are needed.

Once the Rotterdam Fire Department and other emergency services arrive at the scene, the role of the entire in-house team shifts to the role of support and guidance. This doesn’t mean however that the cooperation between the in-house team and the fire department is less intensive, and many team members remain active or on-call during the remainder of the emergency situation.

It is extremely important to have clear and rigid agreements about which party is in charge and when: the relationship between the security staff of the Delftse Poort and the city emergency services are very tight, and the annual full-scale fire drill serves a dual purpose of maintaining this relationship.
B.5 Delftse Poort: input variables

In this section the necessary data is provided for the calculations.

B.5.1 General input variables

A number of general input variables are needed to calculate the egress times. The assistance provided by ING Facility management ops / Security liaison of the building has provided the following data:

As pointed out in paragraph B.2.2, one of the building’s defining features is the transition from the low-rise zone to the high-rise zone. The highest tower (DP1) has two separate lift groups in two separate lobbies: the low-rise lifts and the part of the core that houses them stop above the low-rise zone to make room for office space. Tower DP2 has one central lift group that services the entire tower.

The low-rise zones of both buildings each have 3 emergency stairwells. When the low-rise zone ends, 2 emergency stairwells remain: this means that the entire population of the high-rise zone will use only two out of three emergency stairwells! If one also assumes that the three stairwells in the low-rise section each handle a third of the floor population, an important observation is that the two stairwells that reach up into the high-rise section are used by most of the building population.

B.5.2 Lift input variables:

The manner in which the lifts of the Delftse Poort have been zoned, is important for the calculations regarding the hypothetical possibility of using the different lift evacuation scenarios. Table B.2 describes the building zones.

<table>
<thead>
<tr>
<th>Building function</th>
<th>DP1</th>
<th>DP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical equipment</td>
<td>39 – 40</td>
<td>23 – 24</td>
</tr>
<tr>
<td>High-rise zone</td>
<td>19 – 38</td>
<td>-</td>
</tr>
<tr>
<td>Low-rise zone</td>
<td>6 – 18</td>
<td>6 – 22 (central group)</td>
</tr>
<tr>
<td>Mechanical equipment</td>
<td>4 – 5</td>
<td>4 – 5</td>
</tr>
<tr>
<td>Indoor plaza</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>3-story lobby</td>
<td>Ground floor - 3</td>
<td>Ground floor – 3</td>
</tr>
<tr>
<td>Discharge level</td>
<td>Entrance</td>
<td>Entrance</td>
</tr>
</tbody>
</table>

Table B.2: grouping the Delftse Poort into zones.
Note that in both towers, one lift has the dual function of freight lift and fire-fighter’s lift: this lift isn’t separated from the other lifts though, and in normal mode people can use it. In addition, one of the high-rise lifts in tower DP1 serves as a reserve fire-fighter’s lift.

Table B.3 shows the chosen design parameters for towers DP1 and DP2.

<table>
<thead>
<tr>
<th>(scenario 3a)</th>
<th>DP1</th>
<th>DP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of discharge level:</td>
<td>Ground floor (floor 0)</td>
<td>Ground floor (floor 0)</td>
</tr>
<tr>
<td>Local lift group zones:</td>
<td>LR: floor 6 – 18</td>
<td>Central group: floor 6 – 22</td>
</tr>
<tr>
<td>HR: floor 19 – 38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floors bottom zone – top zone:</td>
<td>6-17= 12</td>
<td>18-38= 21</td>
</tr>
<tr>
<td>6-10= 5</td>
<td>11-22= 12</td>
<td></td>
</tr>
<tr>
<td>Population bottom zone – top zone:</td>
<td>1260</td>
<td>1205</td>
</tr>
<tr>
<td>525</td>
<td>710</td>
<td></td>
</tr>
<tr>
<td>Rendez-vous level at:</td>
<td>Floor 18</td>
<td>Floor 11</td>
</tr>
<tr>
<td>Number of lifts available at rendez-vous level:</td>
<td>6 LR lifts</td>
<td>6 CG lifts</td>
</tr>
<tr>
<td>3 HR lifts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average lift speed:</td>
<td>6.5 m/s (both HR &amp; LR)</td>
<td>6.5 m/s</td>
</tr>
<tr>
<td>Lift weight capacity (passenger lifts):</td>
<td>900 kg</td>
<td>900 kg</td>
</tr>
<tr>
<td>Fire-fighter’s lifts:</td>
<td>1 HR / freight lift</td>
<td>1 CG / freight lift</td>
</tr>
<tr>
<td>1 HR lift (reserve)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lift speed (freight lifts):</td>
<td>3.5 m/s</td>
<td>3.5 m/s</td>
</tr>
<tr>
<td>Lift weight capacity (freight lifts):</td>
<td>1200 kg</td>
<td>1200 kg</td>
</tr>
</tbody>
</table>

Table B.3: Lift design parameters used for the Delftse Poort (calculation scenario 3a).

For the Delftse Poort, only scenario 3a will be explored (besides fractional evacuation): the total building height is only 150 meters and the building itself already has been divided in two sections by design. For tower DP1, the highest landing floor of the low-rise lift group determines the rendez-vous level. For tower DP2 the rendez-vous level can be manipulated to create the shortest egress time, as the lifts of the central lift group have landing doors at all floors. For clarity reasons and because floors 6-11 house much more people than the values used for calculations for the Dutch building environment (105 people/floor instead of 38-48 people/floor), the rendez-vous level has been placed on the highest floor of the low-rise level (just like in DP1). This means that the rendez-vous floors themselves house 105 building occupants and that all floors above them each house 55 persons.

Note that the current building design wouldn’t allow for evacuation via the ‘normal’ lifts to the ground floor, as only the fire-fighter’s lift and reserve lift have landing doors on the ground floor. During normal operation all building occupants use the escalators to ascend to the indoor plaza on the third floor as an assembly area, with all lift landing doors available there. In this hypothetical evacuation scenario though, the ground floor lobby is assumed to have extra landing doors for all lifts for emergency egress.

B.6 Data provided by the evacuation drills

Besides the data for the calculations, data regarding real life experience of evacuations are needed for comparison. In the case of the Delftse Poort, this data has been provided via evacuation drills.

B.6.1 Data from evacuation drills

The Delftse Poort staff do not conduct fire drills for the entire building at once: instead, they conduct drills per section of the building, in order to minimise the disruption of work for the company. The drills are divided as followed:
- DP0 + DP1 low: evacuation of the low-rise section and section DP1.
- DP1 high: evacuation of the high-rise section of DP1 (floors 19 t/m 38).
- DP0 + DP2: evacuation of the low-rise section and tower DP2.
This means that there are no recorded times available regarding evacuation times for the entire building at once. The data from the drills has been summarized in tables B.4 and B.5.

<table>
<thead>
<tr>
<th>Drill</th>
<th>Rally signal</th>
<th>Evac signal first 5 floors</th>
<th>Evac signal second 5 floors</th>
<th>Evac signal last floors</th>
<th>Signal for drill ending + check</th>
<th>Total evacuation time</th>
<th>Estimated vertical egress time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill June 18 2009 (DP1 + low-rise)</td>
<td>14:02</td>
<td>14:05</td>
<td>14:06</td>
<td>14:07</td>
<td>14:31</td>
<td>29 minutes</td>
<td>14-17 minutes</td>
</tr>
</tbody>
</table>

Table B.4: Evacuation times Delftse Poort (tower DP1), recorded via drills.

<table>
<thead>
<tr>
<th>Drill</th>
<th>Rally signal</th>
<th>Evac signal first 5 floors</th>
<th>Evac signal second 5 floors</th>
<th>Evac signal last floors</th>
<th>Signal for drill ending + check</th>
<th>Total evacuation time</th>
<th>Estimated vertical egress time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill June 11 2009 (DP2 + low-rise)</td>
<td>10:32</td>
<td>10:36</td>
<td>–</td>
<td>–</td>
<td>10:52</td>
<td>20 minutes</td>
<td>8-12 minutes</td>
</tr>
</tbody>
</table>

Table B.5: Evacuation times Delftse Poort (tower DP2), recorded via drills.

Because the drills have been conducted separately, the data must be emulated to model a full-scale building evacuation. In addition, the recorded times include inspection times and end when the “all clear” signal has been given. The actual vertical egress time via the stairs therefore cannot always be derived directly from the data provided by the drills. Discussions with mister Huib van der Sluis revealed however that we can estimate the time for stair egress time somewhere between 11-17 minutes. This means that we can estimate the egress time via the stairs: these estimates have been added in the above tables.

Note that one very interesting feature is the one-minute time period between the evacuation per groups of five floors. These interludes cause the emergency stairwells to be less cluttered, allowing room for the ‘fast’ evacuees to descend more freely before they catch up with the stragglers from the group that started evacuating one minute before them. Building occupants have reported this method to be more comfortable than drills where everybody spilled into the emergency stairwells at the same time.

The above tables provide data for two towers, which can be compared to the predictions calculated by the models. One final remark is that, in case of a fire alarm, the main alarm signal (slow-whoop) goes off immediately at the incident floor + two floors up + one floor down; the other building floors receive the pre-alarm and rally signal first, as explained above.
B.7 Comparing building evacuation times: drills versus models

After having given background information about the building and narrowing down the required data for the calculations, a comparison is given between the data that is available via real life evacuation drills and the evacuation times predicted by the models described in this thesis.

B.7.1 Comparing the total pedestrian egress times

Like with the WTC casus, the remaining occupants can be predicted by entering the input values into the calculation models. The results can provide an answer to one of the main questions of this thesis: which method is more accurate, the traditional method or the method with the proposed additional factors? Plotting the calculated egress curve (for both the traditional method and the added factors) yields the following results:

Figure B.9 shows that the difference between the traditional method and the method with the factors proposed in this thesis is rather marginal. The results, which fit well into the other calculations made for 150-meter tall office buildings, are compared with the evacuation drill results in table B.6:

The comparative results are strikingly similar: the given time frames for egress times during the drills mark more or less the area between the traditional calculation results and the results with added factors. One could therefore term this difference as the “level of uncertainty” of the necessary egress time for the Delftse Poort.

One thing to keep in mind is that the differences between the two calculation methods is still relatively small and that the real life data regarding the stair egress times isn’t exactly known (which can give room for biased interpretation of this data).
In the end though the additional factors do indeed seem to be useful: instead of outright replacing the traditional method, the combination traditional calculation and the calculation + factors appear to plot an area in which the expected egress time for a building can be found.

**B.7.2 Evacuating the Delftse Poort via lifts: fractional (scenario 1a/1b) and scenario 3a**

The theoretical egress times for the Delftse Poort have been calculated to show how long it would take to evacuate the office building towers using a rendez-vous level halfway up and shuttling down with lifts (scenario 3a). The calculation results have been summarized in table A.9:

<table>
<thead>
<tr>
<th>Input variable:</th>
<th>Delftse Poort DP1</th>
<th>Delftse Poort DP2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low-rise zone</td>
<td>high-rise zone</td>
</tr>
<tr>
<td>Evacuation time (scenario 0, stairs only):</td>
<td>15 / 18</td>
<td>8 / 8</td>
</tr>
<tr>
<td>Evacuation time (scenario 1, fractional, stair egress time):</td>
<td>15 / 17</td>
<td>7 / 7</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3a, stairs):</td>
<td>7 / 9</td>
<td>7 / 7</td>
</tr>
<tr>
<td>Estimated evacuation time (scenario 3a, lifts):</td>
<td>~ 18 / 13</td>
<td>~ 14 / 11</td>
</tr>
</tbody>
</table>

(Also using fire-fighter’s lifts for equation)

**Table B.7: Estimated evacuation times for DP1 and DP2. Note that the estimated stair egress times include both the traditional calculation method and the method with additional factors.**

When comparing the egress times via stairs only and scenario 3a, it becomes clear that the waiting times at the rendez-vous floors are too long to provide a notable advantage. For the 151-meter high DP1, the total evacuation time would be 1-4 minutes shorter if all lifts are allowed to be used, but that the evacuation time for DP2 (103 meters) remains too long.

**B.8 Conclusions regarding the Delftse Poort**

The found results are in line with the calculations made in chapter 11 and Appendix C: 100-meter tall buildings are still too low to warrant any strategies other than fractional evacuation and at 150 meters a pivotal point can be seen where the evacuation times using lifts, start to become shorter.

Even the relatively high populations per floor of the Delftse Poort didn’t create notably longer evacuation times than found in the calculations of chapter 11. This could be attributed (partly) to the third stairwell in the low-rise section, the amount of floors without office space (Mechanical equipment floors etc) or perhaps that the stairwells are wider than the minimum required values, which have been used in the design calculations.

When regarding the validity of the calculation method using additional factors, the results of this test case showed that the real life data marks more or less the area between the traditional calculation results and the results with added factors. One possibility could be to use a combination of the traditional calculation and the calculation + factors to plot an area in which the expected egress time for a building can be found.
Appendix C

Calculations using the evacuation models
C CALCULATIONS USING THE EVACUATION MODELS

In this appendix, the different evacuation models are compared in regard to their respective evacuation times. In order to do this, a number of fictitious buildings have been “designed”, providing more insight what influence design factors like the building function, population per floor and building height have on evacuation times. Using the models described in chapter 10 of this thesis, the evacuation times of all evacuation scenarios have been calculated. Due to the large number of calculations involved, these calculations were made using a spreadsheet program.

C.1 Creating the input values: the virtual buildings

In order to calculate evacuation times, one needs buildings or, more in particular, the building characteristics needed for these calculations. In this case Peutz and Deerns, the two engineering & consultancy companies where I followed my internship, created the characteristics of a number of fictitious buildings: based on these characteristics, the lift design specialist Jochem Wit (Deerns) constructed designs of a few lift configurations for each building. The building specifications have been defined according to the values given in table C.1. These values have been chosen specifically to represent common values found in the Netherlands.

<table>
<thead>
<tr>
<th>Building function:</th>
<th>Residential</th>
<th>Hotels</th>
<th>Office buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total building height:</strong></td>
<td>All functions: 100m, 150m, 250m.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Population per floor:</strong></td>
<td>100m: 4, 20 persons</td>
<td>100m: 20 persons</td>
<td>100m: 30, 35, 40 persons</td>
</tr>
<tr>
<td></td>
<td>150m: 16, 22 persons</td>
<td>150m: 24 persons</td>
<td>150m: 32, 40, 48 persons</td>
</tr>
<tr>
<td></td>
<td>250m: 20, 24 persons</td>
<td>250m: 30 persons</td>
<td>250m: 50, 60, 70 persons</td>
</tr>
<tr>
<td><strong>Floor height:</strong></td>
<td>3,0m</td>
<td>3,3m</td>
<td>3,6m</td>
</tr>
<tr>
<td><strong>Number of floors:</strong></td>
<td>100m: 30 floors</td>
<td>100m: 24 floors</td>
<td>100m: 24 floors</td>
</tr>
<tr>
<td></td>
<td>150m: 44 floors</td>
<td>150m: 36 floors</td>
<td>150m: 37 floors</td>
</tr>
<tr>
<td></td>
<td>250m: 75 floors</td>
<td>250m: 68 floors</td>
<td>250m: 64 floors</td>
</tr>
<tr>
<td><strong>Building skirt height:</strong></td>
<td>100m: 10m</td>
<td>100m: 20,8m</td>
<td>100m: 13,6m</td>
</tr>
<tr>
<td></td>
<td>150m: 18m</td>
<td>150m: 21,3m</td>
<td>150m: 16,8m</td>
</tr>
<tr>
<td></td>
<td>250m: 25m</td>
<td>250m: 25,6m</td>
<td>250m: 19,6m</td>
</tr>
<tr>
<td><strong>Floors (top) with half population</strong></td>
<td>All functions: 100m: 3 floors</td>
<td>100m: 4 floors</td>
<td>100m: 3 floors</td>
</tr>
<tr>
<td></td>
<td>150m: 4 floors</td>
<td>150m: 5 floors</td>
<td>150m: 4 floors</td>
</tr>
<tr>
<td></td>
<td>250m: 6 floors</td>
<td>250m: 7 floors</td>
<td>250m: 6 floors</td>
</tr>
</tbody>
</table>

Table C.1: Building specifications for the fictional building design set.

As shown above, the buildings have been categorized by their function: residential buildings, hotels and office buildings. The second main category is the building height, which is either 100, 150 or 250 meters high. This determines for each building function the number of floors and the height of the skirt of the building. High-rise buildings usually have at least one floor that serves as a general entrance, with room for a reception, loading docks, service rooms and even shopping areas: this communal area is referred to as the building “skirt”. In this case the building skirts are a convenient ‘buffer’, used to accommodate the exact building height; another, more important reason is that people need to reach the ground level in case of evacuation. The time needed to travel that extra distance shouldn’t be ignored both for lift evacuation calculations and when using the stairs.

One important difference between numbers in the Netherlands and, for instance, the United States of America is that population values per floor are lower: this has to do with the Dutch building codes, that require that work places are situated at a maximum of 7,5 meters away from the windows (due to daylight requirements). This limits building dimensions and thus floor populations in the Netherlands.

Note that the building designs have included a number of floors that are assumed to be populated at half their total capacity. This is a common way to determine the building population and thus the necessary lift capacity. In the calculations for building...
evacuation however, the buildings have been assumed to be fully occupied (in part because this conservative approach allowed for less complicated calculations).

Based on the information given above, a number of designs have been calculated for the lift configurations. In order to provide better insight, most buildings even have at least two designs for their lift groups: usually it means that the building can be serviced by either one central lift group or that the lifts have been divided into a low-rise and high-rise lift group.

Some of the designs have not been developed: this explains why, for instance, the numbering in table C.2 starts with design #3 rather than design #1. The omitted designs were either not realistic or they were scrapped for practical reasons. Originally the designs included a height of 70 meters for instance, but their additional value (relatively low compared to the 100m designs) didn’t warrant the time needed to calculate these additional designs.

C.1.1 Residential buildings

Table C.2 provides an overview of the residential building designs:

<table>
<thead>
<tr>
<th>Number</th>
<th>Building Height</th>
<th>Population per floor</th>
<th>Total # of floors</th>
<th>Lift zoning method (plus zone floors)</th>
<th># of lifts, lift speed</th>
<th>Weight capacity</th>
<th>Quality of lift service</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a</td>
<td>100 m</td>
<td>14 pers.</td>
<td>30 floors</td>
<td>Central</td>
<td>1-30</td>
<td>2,5 m/s</td>
<td>1000 kg</td>
</tr>
<tr>
<td>3b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4a</td>
<td></td>
<td>20 pers.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5a</td>
<td>150 m</td>
<td>16 pers.</td>
<td>44 floors</td>
<td>Central</td>
<td>1-44</td>
<td>3,0 m/s</td>
<td>1000 kg</td>
</tr>
<tr>
<td>5b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6a</td>
<td></td>
<td>22 pers.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7a</td>
<td></td>
<td>16 pers.</td>
<td></td>
<td>low-rise</td>
<td>1-22</td>
<td>2.5 m/s</td>
<td>1000 kg</td>
</tr>
<tr>
<td>7b</td>
<td></td>
<td></td>
<td></td>
<td>high-rise</td>
<td>23-44</td>
<td>5.0 m/s</td>
<td>1000 kg</td>
</tr>
<tr>
<td>8a</td>
<td></td>
<td>22 pers.</td>
<td></td>
<td>low-rise</td>
<td>1-22</td>
<td>2.5 m/s</td>
<td>1000 kg</td>
</tr>
<tr>
<td>8b</td>
<td></td>
<td></td>
<td></td>
<td>high-rise</td>
<td>23-44</td>
<td>5.0 m/s</td>
<td>1000 kg</td>
</tr>
<tr>
<td>11a</td>
<td>250 m</td>
<td>20 pers.</td>
<td>75 floors</td>
<td>low-rise</td>
<td>1-38</td>
<td>3.5 m/s</td>
<td>1000 kg</td>
</tr>
<tr>
<td>11b</td>
<td></td>
<td></td>
<td></td>
<td>high-rise</td>
<td>39-75</td>
<td>4.5 m/s</td>
<td>1000 kg</td>
</tr>
<tr>
<td>12a</td>
<td></td>
<td>24 pers.</td>
<td></td>
<td>low-rise</td>
<td>1-38</td>
<td>4.0 m/s</td>
<td>1275 kg</td>
</tr>
<tr>
<td>12b</td>
<td></td>
<td></td>
<td></td>
<td>high-rise</td>
<td>39-75</td>
<td>6.0 m/s</td>
<td>1275 kg</td>
</tr>
</tbody>
</table>

Table C.2: Lift configuration designs for residential buildings (based on height, population per floor and the desired quality of service)

The lifts for residential buildings have been designed with a 5% uppeak handling capacity. The table above illustrates how low the relative floor population is when considering residential buildings. This means that, even for 250-meter high buildings, no sky lobbies are needed (at least when regarding the lift handling capacity; at these heights, other constraints like maximum water pressure and ventilation capacities require a floor or two that are reserved for installations).

The quality of the lift configuration refers to the preference of an average person, regarding the waiting time in particular. With housing the design choices have been typed as “economical”, “good”, and “luxurious”. As table C.2 shows, the quality level can have quite an influence on lift design. There are a few other variables that are affected by the quality level, like the difference between the maximum lift capacity and the percentage of people (in terms of weight) that actually stand inside the lift (people in office buildings are used to a higher density, while people in hotels and residential buildings tend to value their personal space more).
### C.1.2 Hotel buildings

Table C.3 provides an overview of the hotel building designs:

<table>
<thead>
<tr>
<th>Number</th>
<th>Building Height</th>
<th>Population Per floor</th>
<th>Total # of floors</th>
<th>Lift zoning (plus zone floors)</th>
<th># of lifts, lift speed</th>
<th>weight capacity</th>
<th>Quality of lift service</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>100 m</td>
<td>24 pers.</td>
<td>24 floors</td>
<td>Central 1-24</td>
<td>4</td>
<td>3.5 m/s</td>
<td>1275 kg Luxurious</td>
</tr>
<tr>
<td>3</td>
<td>150 m</td>
<td>39 pers.</td>
<td>39 floors</td>
<td>Central 1-39</td>
<td>7</td>
<td>4.5 m/s</td>
<td>1275 kg Luxurious</td>
</tr>
<tr>
<td>4</td>
<td>150 m</td>
<td>39 pers.</td>
<td>39 floors</td>
<td>low-rise 1-21</td>
<td>4</td>
<td>3.0 m/s</td>
<td>1275 kg good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>high-rise 22-39</td>
<td>4</td>
<td>5.0 m/s</td>
<td>1275 kg good</td>
</tr>
<tr>
<td>4 ZZ</td>
<td>shuttle</td>
<td></td>
<td></td>
<td>Central 23-39 shuttle to 23</td>
<td>2</td>
<td>3.0 m/s</td>
<td>1275 kg Luxurious</td>
</tr>
<tr>
<td>6a Z1</td>
<td>250 m</td>
<td>30 pers.</td>
<td>68 floors</td>
<td>Central 1-34</td>
<td>7</td>
<td>4.5 m/s</td>
<td>1275 kg Luxurious</td>
</tr>
<tr>
<td>6b Z1</td>
<td>250 m</td>
<td>30 pers.</td>
<td>68 floors</td>
<td>low-rise 1-17</td>
<td>4</td>
<td>2.5 m/s</td>
<td>1275 kg good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>high-rise 18-34</td>
<td>4</td>
<td>4.5 m/s</td>
<td>1275 kg good</td>
</tr>
<tr>
<td>6a Z2</td>
<td>250 m</td>
<td>40 pers.</td>
<td>68 floors</td>
<td>Central 37-68</td>
<td>5</td>
<td>5.0 m/s</td>
<td>1600 kg good</td>
</tr>
<tr>
<td>6b Z2</td>
<td>250 m</td>
<td>40 pers.</td>
<td>68 floors</td>
<td>low-rise 37-54</td>
<td>3</td>
<td>2.5 m/s</td>
<td>1275 kg good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>high-rise 55-68</td>
<td>3</td>
<td>4.0 m/s</td>
<td>1275 kg luxurious</td>
</tr>
<tr>
<td>6 shuttes</td>
<td></td>
<td></td>
<td></td>
<td>shuttle to 37</td>
<td>2</td>
<td>6.0 m/s</td>
<td>1600 kg luxurious</td>
</tr>
</tbody>
</table>

Lifts in hotels have been designed with a 14% uppeak handling capacity: this illustrates the high standards that hotels have in order to keep their guests happy. There are therefore no "economical" lift configurations, just good and better. One important side note is that the shuttle lifts are designed for a 10% handling capacity.

Above a certain height, buildings will probably have multiple functions. This is why in design (4 Z2) the 150m high building has been divided to accommodate a hotel from floor 23 to 39, with exclusive shuttle lifts for the hotel guests. The bottom half could, for instance, be reserved for office space.

### C.1.3 Office buildings

Table C.4a and C.4b provide an overview of the office building designs:

<table>
<thead>
<tr>
<th>Number</th>
<th>Building Height</th>
<th>Population Per floor</th>
<th>Total # of floors</th>
<th>Lift zoning (plus zone floors)</th>
<th># of lifts, lift speed</th>
<th>weight capacity</th>
<th>Quality of lift service</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a</td>
<td>100 m</td>
<td>30 pers.</td>
<td>24 floors</td>
<td>Central 1-18</td>
<td>4</td>
<td>3.5 m/s</td>
<td>1275 kg Good</td>
</tr>
<tr>
<td>4b</td>
<td>150 m</td>
<td>32 pers.</td>
<td>37 floors</td>
<td>Central 1-17</td>
<td>3</td>
<td>3.5 m/s</td>
<td>1275 kg Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>low-rise 13-24</td>
<td>3</td>
<td>3.0 m/s</td>
<td>1275 kg Luxurious</td>
</tr>
<tr>
<td>5a</td>
<td>250 m</td>
<td>40 pers.</td>
<td>68 floors</td>
<td>Low-rise 1-12</td>
<td>4</td>
<td>3.5 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Central 1-24</td>
<td>4</td>
<td>3.5 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td>6b</td>
<td>250 m</td>
<td>40 pers.</td>
<td>68 floors</td>
<td>Low-rise 13-24</td>
<td>3</td>
<td>3.5 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Central 22-37</td>
<td>4</td>
<td>6.0 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td>7a</td>
<td>210 m</td>
<td>30 pers.</td>
<td>68 floors</td>
<td>Central 1-17</td>
<td>4</td>
<td>3.5 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td>7b</td>
<td>210 m</td>
<td>30 pers.</td>
<td>68 floors</td>
<td>low-rise 22-37</td>
<td>4</td>
<td>3.5 m/s</td>
<td>1600 kg Luxurious</td>
</tr>
<tr>
<td>8a</td>
<td>250 m</td>
<td>40 pers.</td>
<td>68 floors</td>
<td>low-rise 1-17</td>
<td>4</td>
<td>3.5 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Central 1-37</td>
<td>7</td>
<td>6.0 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td>9a</td>
<td>250 m</td>
<td>40 pers.</td>
<td>68 floors</td>
<td>Low-rise 1-17</td>
<td>4</td>
<td>3.5 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Central 22-37</td>
<td>4</td>
<td>6.0 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td>10 Z1</td>
<td>32 pers.</td>
<td></td>
<td>24 floors</td>
<td>Central 1-18</td>
<td>4</td>
<td>3.5 m/s</td>
<td>1000 kg Luxurious</td>
</tr>
<tr>
<td>10 Z2</td>
<td>32 pers.</td>
<td></td>
<td>24 floors</td>
<td>Central 21-37</td>
<td>3</td>
<td>2.5 m/s</td>
<td>1000 kg Luxurious</td>
</tr>
<tr>
<td>10 shuttle</td>
<td></td>
<td></td>
<td></td>
<td>shuttle to 20</td>
<td>2</td>
<td>3.0 m/s</td>
<td>1275 kg Luxurious</td>
</tr>
<tr>
<td>11 Z1</td>
<td>100 m</td>
<td>40 pers.</td>
<td>40 floors</td>
<td>Central 1-18</td>
<td>4</td>
<td>3.5 m/s</td>
<td>1275 kg Luxurious</td>
</tr>
<tr>
<td>11 Z2</td>
<td>100 m</td>
<td>40 pers.</td>
<td>40 floors</td>
<td>Central 21-37</td>
<td>3</td>
<td>2.5 m/s</td>
<td>1275 kg Luxurious</td>
</tr>
<tr>
<td>11 shuttle</td>
<td></td>
<td></td>
<td></td>
<td>shuttle to 20</td>
<td>2</td>
<td>3.0 m/s</td>
<td>1600 kg Luxurious</td>
</tr>
<tr>
<td>12 Z1</td>
<td>100 m</td>
<td>48 pers.</td>
<td>68 floors</td>
<td>Central 1-18</td>
<td>4</td>
<td>3.0 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td>12 Z2</td>
<td>100 m</td>
<td>48 pers.</td>
<td>68 floors</td>
<td>Central 21-37</td>
<td>3</td>
<td>3.0 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td>12 shuttle</td>
<td></td>
<td></td>
<td></td>
<td>shuttle to 20</td>
<td>2</td>
<td>4.0 m/s</td>
<td>1600 kg Luxurious</td>
</tr>
<tr>
<td>16a Z1</td>
<td>250 m</td>
<td>50 pers.</td>
<td>64 floors</td>
<td>Central 1-31</td>
<td>7</td>
<td>5.0 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td>16b Z1</td>
<td>250 m</td>
<td>50 pers.</td>
<td>64 floors</td>
<td>Low-rise 1-19</td>
<td>4</td>
<td>3.0 m/s</td>
<td>1275 kg Good</td>
</tr>
<tr>
<td>16a Z2</td>
<td>250 m</td>
<td>50 pers.</td>
<td>64 floors</td>
<td>low-rise 35-64</td>
<td>6</td>
<td>4.0 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td>16b Z2</td>
<td>250 m</td>
<td>50 pers.</td>
<td>64 floors</td>
<td>Low-rise 35-64</td>
<td>3</td>
<td>2.5 m/s</td>
<td>1600 kg Good</td>
</tr>
<tr>
<td>16 shuttle</td>
<td></td>
<td></td>
<td></td>
<td>shuttle to 34</td>
<td>4</td>
<td>5.0 m/s</td>
<td>1600 kg Luxurious</td>
</tr>
</tbody>
</table>

Table C.4a: Lift configuration designs for office buildings (based on height, population per floor and the desired quality of service)
The lifts for office buildings have been designed with a 12% uppeak handling capacity: companies generally require a good, efficient lift service for their employees and their customers. The above table with designs is quite long: the relatively high population per floor warrants the possibility of a low- and high-rise option for every design and the 250-meter high version has been calculated with three different population numbers. In addition, the 150-meter high buildings have been considered with a sky lobby scenario (designs 10, 11 and 12). In the Netherlands however, actual buildings of 150 meters do not have sky lobbies; these designs should therefore be considered theoretical, unless when considering to divide the building in two for different functions like a hotel for the top half of the building.

### C.2 Calculation results for residential buildings

The calculation results for residential buildings were in the lines of the expectations. There are a number of interesting observations to be made from these results, which will be explained together with the tables of data.

The results have been calculated for all evacuation scenario’s except scenario 4b (free choice between stairs or lifts + behaviour influenced by incident location): this scenario is too complicated for ‘straightforward’ calculations and should better be left aside for simulation programs. Scenario 4a (free choice between stairs or lifts) should technically be calculated via a simulation program as well, but a few assumptions allow for at least a rough estimate. These assumptions for scenario 4a are:

- The ratio for personal choice has been assumed to be that 50% of the occupants choose to use the stairs and 50% choose the lifts, regardless of their height in the building.
- In the stairwells the population density is low enough to allow for a Free Flow situation. This means that the (maximum) time needed to head down to safety is equal to the distance between the top floor and, in the case of this particular calculation, the skirt level of the building (in practice it should be ground level).
### Table C.5a: Calculation results per scenario for residential buildings.

<table>
<thead>
<tr>
<th>Design number</th>
<th>Evacuation scenario</th>
<th>Pedestrian traditional</th>
<th>Pedestrian + factors</th>
<th>Lifts</th>
<th>Bottleneck time</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a</td>
<td>0 – Stairs only</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1a – Fractional (fire dept.)</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>6</td>
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<tr>
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<td>2 – Lifts only</td>
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<tr>
<td></td>
<td>3a – Transfer floors</td>
<td>3</td>
<td>X</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3b – Sub-transfer floors</td>
<td>3</td>
<td>X</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4a – Free choice lifts/stairs</td>
<td>6</td>
<td>6</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3b</td>
<td>0 – Stairs only</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<tr>
<td></td>
<td>1a – Fractional (fire dept.)</td>
<td>4</td>
<td>4</td>
<td>6</td>
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<tr>
<td></td>
<td>2 – Lifts only</td>
<td>2</td>
<td>X</td>
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<td></td>
<td>3a – Transfer floors</td>
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<td></td>
<td>3b – Sub-transfer floors</td>
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</tr>
<tr>
<td></td>
<td>4a – Free choice lifts/stairs</td>
<td>6</td>
<td>6</td>
<td>X</td>
<td>X</td>
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<td>5</td>
<td>5</td>
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<td>-</td>
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<tr>
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<td>2 – Lifts only</td>
<td>2</td>
<td>X</td>
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<td></td>
<td>3a – Transfer floors</td>
<td>3</td>
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<tr>
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<td>X</td>
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<td>3</td>
</tr>
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<td></td>
<td>4a – Free choice lifts/stairs</td>
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### Table C.5b: Calculation results per scenario for residential buildings (continued).

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<th>Design number</th>
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<th>Pedestrian traditional</th>
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<th>Lifts</th>
<th>Bottleneck time</th>
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<tr>
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<td>2 – Lifts only</td>
<td>2</td>
<td>X</td>
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</tr>
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<td>X</td>
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<td>X</td>
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</tr>
<tr>
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<td>4a – Free choice lifts/stairs</td>
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<td>7b</td>
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<td>2</td>
<td>X</td>
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<td>3</td>
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<tr>
<td></td>
<td>3a – Transfer floors</td>
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<td>X</td>
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<td>3b – Sub-transfer floors</td>
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<td>X</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4a – Free choice lifts/stairs</td>
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<td>9</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8a</td>
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<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1a – Fractional (fire dept.)</td>
<td>6</td>
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<td>7</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>1b – Fractional (ASS team)</td>
<td>6</td>
<td>-</td>
<td>3</td>
<td>3</td>
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<tr>
<td></td>
<td>2 – Lifts only</td>
<td>2</td>
<td>X</td>
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<tr>
<td></td>
<td>3a – Transfer floors</td>
<td>3</td>
<td>X</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3b – Sub-transfer floors</td>
<td>3</td>
<td>X</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4a – Free choice lifts/stairs</td>
<td>9</td>
<td>9</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8b</td>
<td>0 – Stairs only</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1a – Fractional (fire dept.)</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>1b – Fractional (ASS team)</td>
<td>6</td>
<td>-</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2 – Lifts only</td>
<td>2</td>
<td>X</td>
<td>3</td>
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<tr>
<td></td>
<td>3a – Transfer floors</td>
<td>3</td>
<td>X</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3b – Sub-transfer floors</td>
<td>3</td>
<td>X</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4a – Free choice lifts/stairs</td>
<td>9</td>
<td>9</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
The above tables show the sheer volume of the generated data (which has been generated using Excel sheets): in order to provide a better overview of the results, the most defining characteristics will be illustrated in the following paragraphs.

C.2.1 Residential buildings: general remarks (scenario 1b and 3a)
In the tables C.5, evacuation scenario 1b (fractional evacuation by the ASS team) has been omitted from the results. The reason for this is that residential buildings have been assumed not to have Appointed Safety Supervisors: this automatically entails that this scenario isn’t applicable for residential buildings.

In the case of evacuation scenario 3a (evacuation using rendez-vous levels at the transfer floors), tables C.5 show no results for central lift groups and show no lift results (value = 0) for low-rise sections. In case of a central lift group, there are no low-rise and high-rise groups: therefore there are no transfer floors, as there is no need for a level where a person can switch between lift groups without needing to travel all the way to the entrance lobby. Note that the building still can be divided into smaller sections though: in scenario 3b the building (zone) is divided into two halves and the building occupants of the top half assemble at a rendez-vous level, where the lifts will shuttle them further down to ground level. This seems like the same situation as 3a for a low-rise / high-rise building, save for the fact that the zoning method of the lift group is quite different. To some, this difference might be considered a mere technicality.

In case of a low-rise / high-rise zoning and scenario 3a, the building occupants of the entire low-rise zone use the stairwell, and the low-rise lifts help the high-rise lifts to shuttle down the occupants of the high-rise section: therefore only the stairwell egress time is relevant for the low-rise section in scenario 3a.

It should be self-explanatory that in scenario 0 (stairs only) lifts aren’t applicable, and that in scenario 2 (lifts only) stair egress isn’t applicable.

C.2.2 Influence of height and population density on pedestrian movement
The calculated values of the residential building models in particular showed that the stairwells simply weren’t full enough to support a Full Flow calculation: this was determined by the fact that the minimum amount of time needed to walk from the top floor to building skirt level was longer than the values derived from the capacity-based calculations. This will be explained by the example shown in table C.6:

<table>
<thead>
<tr>
<th>Design number</th>
<th>Evacuation scenario</th>
<th>Pedestrian traditional</th>
<th>Pedestrian + factors</th>
<th>Lifts</th>
<th>Bottleneck time</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a</td>
<td>0 – Stairs only</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1a – Fractional (fire dpt.)</td>
<td>4</td>
<td>4</td>
<td>x</td>
<td>X</td>
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<tr>
<td></td>
<td>1b – Fractional (ASS team)</td>
<td>4</td>
<td>4</td>
<td>x</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>2 – Lifts only</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3a – Transfer floors</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3b – Sub-transfer floors</td>
<td>3</td>
<td>3</td>
<td>x</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>4a – Free choice lifts/stairs</td>
<td>6</td>
<td>6</td>
<td>x</td>
<td>X</td>
</tr>
</tbody>
</table>

Table C.6: Calculation results: example residential buildings, nr. 3a.

This table shows the results of evacuation type 3a (residential, 100m high, 14 occupants per floor, normal lift configuration, central zoning). Studying the first column reveals that the null option (stairs only) yields a stair egress time of 5 minutes; with fractional evacuation (1a and 1b) this time even drops to 4 minutes. Option 4a (free choice), where the stair egress time is calculated using the simple (Free Flow) method of dividing the travel distance by the standard pedestrian speed via stairs, yields a 6-minute evacuation time.
The evacuation times of options 0 and 1 are generated using the Full Flow method: this method can basically be compared to a storage vat of which the content flows out of the tap until the vat is empty. In this analogy the content is represented by the building population, and the tap is represented by the stairwell, which is assumed to be the bottleneck during evacuation. In this particular example however, the storage vat would be empty in 5 minutes, while it would take a "water droplet" or person at least 6 minutes to walk from the top floor to ground level.

The interpretation of this discrepancy is that the stairwells will never reach a Full Flow situation, i.e. the population density inside the stairwells will remain below 2.0 persons/m². The only reason to design two emergency stairwells in this example building is that the Dutch building code demands at least two emergency stairwells for all buildings of this height, regardless of the building population density.

C.2.3 Difference between traditional results and the proposed additional factors

The same table (C.6) shows the differences between the ‘traditional’ calculation method and the method proposed in this thesis, which adds three additional factors: a demographic factor, a fatigue factor and a risk factor. In these calculations the demographic factor has been set to 1 (no influence). The other two factors start causing a longer evacuation time after 5 minutes.

With this in mind, it is logical to see that the differences between the traditional and the proposed method is minimal: only higher buildings with larger populations start to show differences in the results. This also shows the advantages of dividing a building in sections like in scenarios 3a and 3b: the decrease in travel distance nullifies any influence caused by these factors, making the traditional calculations more dependable. In other words: if the building occupants don’t need to use the stairs all the way down from the top of (high) buildings but only need to go half way down (for instance), effects like fatigue are reduced.

C.2.4 Fire-fighter’s lifts integrated in the standard lift group.

In order to keep building designs as cheap as possible by minimizing the amount of lifts, many interest groups in the Netherlands are pushing for the possibility to integrate the fire-fighter’s lifts into the normal lift group. On the other side, a number of officials from fire departments demand that the fire-fighter’s lifts may only be used by fire-fighters: in case of an emergency, these lifts remain in place at ground level, reserved for the fire department: this means that these lifts can not be used by anybody else, even in the time during which the fire department haven’t arrived on scene yet. In addition the officials demand that at least two fire-fighter’s lifts should be present in the building (if one of the lifts isn’t working or has been shut down for maintenance, the fire department has a backup lift). Fire-fighter’s lifts need to service all floors, so these lifts are always either part of the central lift group or the high-rise lift group.

The combination of these three prerequisites results in a decrease of the available lifts by two. Residential lifts in particular have a relatively low building population and therefore a relatively low number of lifts. The result is quite clear when studying the tables C.5: the evacuation times with central lift groups or high-rise lift groups are much higher, to the point that evacuation using lifts would be pointless. The calculations of designs 3, 4, 7 and 8 even would be impossible, as the lift groups there consist of two lifts in total. Only fractional evacuation by the fire department would be a viable option in these cases.

This result could be a reason to opt for separate fire-fighter’s lifts: by using the freight/service lift(s) for a dual function as fire-fighter’s lift, the normal lift group would have at least one more lift available for ‘civilian’ evacuation. In the case of residential buildings, one can question the economic feasibility and the added value though of
installing an extra, separate lift for the sole purpose of separating the fire-fighter’s lifts from the normal lift group. Reaction times in residential buildings are relatively long (giving the fire department ample time to arrive and take control), and the pedestrian stair egress times are relatively short.

A second, more viable option would be to allow the use of fire-fighter’s lifts for ‘civilian’ evacuation in the time frame before the arrival of the fire department. With clear, unambiguous policies it should be possible to regulate properly the transition from civilian-controlled evacuation to an evacuation under supervision of the fire department.

**C.2.5 Residential buildings: is total evacuation necessary?**

One final, very important issue is the question whether (total) evacuation is even necessary. Disregarding large catastrophes, fires are the most common incidents. The Dutch building code requires apartments to be constructed as separate compartments with each a sixty-minute fire resistance; in addition all buildings higher than 100 meters are required to have sprinkler installations.

Even without the sprinklers, the fire department will likely be able to keep the fire contained within the apartment where the fire started. In cases like this one, initial evacuation will probably be limited to the incident floor + 2 floors above + 1 floor below.
C.3 Calculation results for hotels

Like for residential buildings, a number of scenarios were created for hotels. These are the calculation results for hotel buildings:

<table>
<thead>
<tr>
<th>Design number</th>
<th>Evacuation scenario</th>
<th>Pedestrian traditional</th>
<th>Pedestrian + factors</th>
<th>Lifts</th>
<th>Bottleneck time</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
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<td>LR / HR</td>
<td>LR / HR</td>
<td>LR / HR</td>
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<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>1a – Fractional (fire dept.)</td>
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<td>7</td>
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Table C.7: Calculation results per scenario for hotels.

Table C.7 shows that the list of calculation results for hotels is shorter than the list for residential buildings. The main reason for this difference is that only one quality level has been assumed for the lift groups in hotels (a combination of good and luxurious). This means that there are less alternatives that need to be calculated.

C.3.1 Hotels: general remarks

Like in residential buildings, evacuation scenario 3a does not apply for buildings with central lift groups, and in the low-rise zones only the stairwell egress time is relevant. It should be self-explanatory that in scenario 0 (stairs only) lifts aren't applicable, and that in scenario 2 (lifts only) stair egress isn't applicable.

Total building evacuation during a fire is more probable in hotels than in residential buildings. Where residential buildings are assumed to be compartmentalised in a robust manner, hotels are likely to have large, communal spaces like restaurants, gyms, bars etcetera. The MGM Grand fire, which has been discussed in chapter 5 of this thesis, is a vivid example of the potential fire hazards that these areas can be. Another reason is that where occupants in residential buildings are primarily responsible to ensure their own safety in case of fire, the clients in hotels become the responsibility of the hotel management. Respective insurance and liability issues can be a strong incentive to evacuate everybody, just to be on the safe side. Once again though, the obligated sprinkler systems should greatly reduce fire propagation.
C.3.2 Influence of height and population density on pedestrian movement

The building population density in hotels is relatively low, but slightly higher than in residential buildings. The first calculation results show that the pedestrian density in the emergency stairwells is roughly the same for both the Free Flow and the Full Flow calculations, which means that congestion problems in these stairwells should be minimal.

Note that hotel building design #6 is divided in two sections by a sky lobby. The stair egress times in scenarios 0, 1a and 1b are values for the entire building; the values for scenarios 3a, 3b and 4a are values for one building section. In other words: in scenarios 0, 1a and 1b the evacuees are assumed to have to use the stairs for the entire building, and in 3a, 3b and 4a they only need to head down to either the sky lobby or to ground level. This means that, when comparing values to check for Full or Free Flow, the values of 3a, 3b and 4a should be doubled to compare the results with 0, 1a and 1b.

C.3.3 Difference between traditional results and the proposed additional factors

Again, the differences between the results of the traditional method and the version with the added factors is minimal and only starts to show for 250m high buildings. Note that at this height it is quite probable that the hotel only covers one building section, and that for instance the bottom half (below the sky lobby) is occupied by apartments or office space.

C.3.4 Shuttle lifts as bottleneck

Hotel design #6 is a 250m high building with a sky lobby that is serviced by shuttle lifts. Shuttle lifts already function quite efficiently, leaving little to no room for shorter egress times in respect to their normal service mode (the calculated egress time is actually even longer than the normal service mode). The result is that, while building sections can be emptied in a time period of as short as 10 minutes, the top half of the building will be empty after 49 minutes when depending on the shuttle lifts.

One positive aspect of this method is that the remaining building population is concentrated in the sky lobby area: this area can be protected by robust compartments, extra equipped with extra ventilation systems, communication systems, food & water or even treatment areas. In addition, the emergency stairwells are empty by the time the fire department arrives. With an egress time of 23 minutes by stairs alone however, the limited handling capacity of these shuttle lifts may be a reason to reject using lifts for evacuation.

In order to create a viable evacuation scenario using lifts, solution are required to boost the handling capacity and shorten the waiting times in the sky lobbies. One possible solution is the use of the separate service / fire fighter’s lifts to shuttle evacuees down from the sky lobby to ground level. Another possibility could be to use the lift group of the building zone below the sky lobby after this lift group has transported the last occupants of the bottom half of the building.
C.4 Calculation results for office buildings

These are the calculation results for office buildings:

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<tr>
<th>Design number</th>
<th>Evacuation scenario</th>
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<th>Pedestrian + factors</th>
<th>Lifts</th>
<th>Bottleneck time</th>
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Table C.8a: Calculation results per scenario for office buildings.

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Table C.8b: Calculation results per scenario for office buildings (continued).
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<td>3b - Sub-transfer floors</td>
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<td>4a - Free choice lifts/stairs</td>
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<tr>
<td>17 Z2CG</td>
<td>Stairs only</td>
<td>32</td>
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<td>93</td>
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<td>4a - Free choice lifts/stairs</td>
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</table>
Tables C.8 show that the list of calculation results for office buildings is by far the longest: for each height, 3 population densities have been calculated and 3 designs including a sky lobby have been calculated for both 150 meters and for 250 meters.

C.4.1 Office buildings: general remarks
Like in residential buildings, evacuation scenario 3a does not apply for buildings with central lift groups, and in the low-rise zones only the stairwell egress time is relevant. It should be self-explanatory that in scenario 0 (stairs only) lifts aren’t applicable, and that in scenario 2 (lifts only) stair egress isn’t applicable.

C.4.2 Influence of height and population density on pedestrian movement
The population densities in the office building designs are all high enough to create a Full Flow situation in the stairwells, although the differences at lower heights and population densities are small.

Once again, it is important to note that the populations per floor are relatively low for buildings in the Netherlands compared to, for instance, U.S. standards, due to the minimum daylight requirements enforced by the Dutch laws regarding the working environment of employees (in Dutch: ARBO Wet).

C.4.3 Difference between traditional results and the proposed additional factors
It is very interesting to discover a pivotal point at 150 meters, where the difference between the traditional calculation method and the method with additional factors starts to manifest itself. The differences here are still quite small, but the calculation results for the 250-meter building designs show large differences. One of the reasons is probably the higher building populations per floor that have been used for these designs.

When regarding the increased population that makes use of the stairwells, it is only fair to assume that, in order to meet the increased capacity needs, a third stairwell needs to be added to the design at one point. For these designs, it is assumed that a third emergency stairwell will be added at 250 meters. The stairwell egress times in this paragraph still assume 2 stairwells for reference purposes, but a version with calculations of 250-meter high office buildings with a third staircase will be discussed further in paragraph C.6 (@@).

C.4.4 Fire-fighter’s lifts integrated in the standard lift group.
As already explained in paragraph C.2.4, the integration of the fire-fighter’s lifts as part of the ‘normal’ lift group decreases the capacity of these lift groups immensely. Table C.8a shows that, in the case of office buildings with a low-rise / high-rise zoning method, evacuation scenario 3b isn’t possible for the high-rise lift group: after subtracting two lifts for the fire department, there simply aren’t enough lifts left to service two rendez-vous levels at once. Proposed solutions for this problem are to either use separate (service) lifts as fire-fighter’s lifts and/or allow the ASS team to use these fire-fighter’s lifts until the fire department arrives to take over.

Paragraph C.5 compares the calculations of the office buildings of 100 and 150 meters: on one side the current calculations are used (where 2 lifts are subtracted from the lift group); the other side sows the respective evacuation times if all lifts in the lift groups are allowed to be used by the ASS team.

One final note: in case of the designs that include a sky lobby, it already has been assumed that the ASS team may make use of all lifts. The reasoning behind this decision is that in a 250-meter high office building that has been separated by a sky lobby, the design includes two separate service lifts that can stop at every single floor, whether it be above, below or at the sky lobby itself.
C.4.5 Shuttle lifts as bottleneck

As with hotels, the shuttle lifts servicing the sky lobby prove to be a bottleneck for office buildings. The suggested examples to shorten the evacuation time include adding the service lifts to shuttle people down from the sky lobby or to use lifts from the zone below the sky lobby.
### C.5 Office buildings: including the fire-fighter’s lifts into the calculations

The calculation results in the previous paragraphs show higher evacuation times when two lifts of the lift group need to be reserved as fire-fighter’s lifts. In this paragraph, the comparative results will be shown when the ASS teams are allowed to use these lifts.

The table below shows the comparative results for 150-meter high office buildings. The left column shows the ‘normal’ results, the right column shows the results when the last two lifts are allowed to be used as well.

<table>
<thead>
<tr>
<th>Design number</th>
<th>Evacuation scenario</th>
<th>Pedestrian + factors</th>
<th>Lifts</th>
<th>Bottleneck time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Evacuation time (s)</td>
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<tr>
<td></td>
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<td>LR / HR</td>
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<td>LR / HR</td>
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<th>Design number</th>
<th>Evacuation scenario</th>
<th>Pedestrian + factors</th>
<th>Lifts</th>
<th>Bottleneck time</th>
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<tr>
<td></td>
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<td>Evacuation time (s)</td>
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<tr>
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<td></td>
<td>LR / HR</td>
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</tbody>
</table>

**Table C.9: Comparative calculation results for office buildings (150m): fire-fighter’s lifts subtracted from the lift groups (left); fire-fighter’s lifts are allowed to be used (right).**

When comparing the results in table C.9, the evacuation times of especially the high-rise lift groups drop dramatically: this shows that using lifts for evacuation (other than fractional evacuation) is only viable if all lifts may be used by the ASS team, in particular for buildings with a low-rise / high-rise lift zoning method.

Even with the use of all lifts, evacuation times are marginally shorter (with scenario 3a (3b for central lift groups) being the fastest method), at least when compared to the traditional approach. When using the additional factors, the egress time in design 9a drops from 19 to 10 minutes: in other words, the evacuation time would be cut in half.
With the results in mind, fractional evacuation might be the best evacuation method for buildings up to 150 meters, although an evacuation scenario with a rendez-vous level halfway up the building has proven itself to be an alternative worth considering. Stair egress times for buildings higher than 150 meters and/or higher building populations than those chosen for these designs become high enough to warrant evacuation using lifts, making 150 meters a pivotal point in Dutch fire safety design.

### C.6 Office buildings: the effects of adding a third stairwell for stair egress times

All stair egress calculations have been conducted with the assumption that the building designs have 2 emergency stairwells. When regarding the increased population that makes use of the stairwells however, it is only fair to assume that, in order to meet the increased capacity needs, a third stairwell needs to be added to the design at one point. The addition of a third stairwell will affect the stair egress time: in order to both present a realistic scenario (3 stairwells) and be able to show the increasing influence of height and population density in respect to congestion for 2 stairwells, the stair egress times for both 2 and 3 stairwells have been calculated for 250-meter high office buildings.

Since stair egress times for Low-rise / high-rise zones are the same as for central lift groups, table C.10 only shows the results for central lift groups.

<table>
<thead>
<tr>
<th>Design number</th>
<th>Evacuation scenario</th>
<th>Pedestrian traditional</th>
<th>Pedestrian + factors</th>
<th>Lifts</th>
<th>Bottleneck time</th>
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<tbody>
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<td>Stairs only</td>
<td>27</td>
<td>51</td>
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<tr>
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<td>2 – Lifts only</td>
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<td>3a – Transfer floors</td>
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<td>3b – Sub-transfer floors</td>
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<td>4a – Free choice lifts/stairs</td>
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<td>17 ZTCG 0</td>
<td>Stairs only</td>
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<tr>
<td>4a – Free choice lifts/stairs</td>
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<tr>
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<td>1b – Fractional (ASS team)</td>
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Table C.10: Comparative calculation results for 250-meter office buildings: 2 stairwells (left) versus 3 stairwells (right).

Table C.10 shows that even though pedestrian egress times are reduced considerably by adding a third stairwell, these egress times are at least twice as long as scenario 3b, where a rendez-vous level has been designed halfway down the building section and the occupants are shuttled down to either the sky lobby or to ground level (depending on which building section they’re in). This shows that buildings with higher population densities in particular can benefit greatly from designs that incorporate evacuation via lifts.

Please note that, although not added here, the egress times needed for the shuttle lift groups to evacuate the sky lobby are still applicable for these buildings and need to be added into the equation.