STATE OF THE ART FIRE SAFETY CONCEPT FOR EVACUATION OF DIFFERENT TYPES OF VULNERABLE PATIENTS IN DUTCH HOSPITALS

Graduation thesis
Delft University of Technology
Faculty of Architecture and the Built Environment
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P.P.N. Hoondert

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Abstract

The fire safety strategy in hospitals is complex, and requires an integrated approach, because of the presence of vulnerable and reliant patients who need assistance during evacuation. The current regulations in the Netherlands seems to be outdated, and don't fulfill the current use and the changing design trends. Design trends of hospitals are changing, shifting towards a healing environment with mostly single patient rooms.

Research into the actual disconnecting times of different types of patients is performed, to determine the total evacuation time per patient. As displayed different phases of the evacuation route are gathered and analysed. With these differing evacuation times, the design can be adapted to the required egress time per specific ward. The evacuation times of patients on a Dialysis, Intensive Care, Neonatal ICU, Heart monitoring, Recovery and a standard nursing ward have been gathered. All patients were connected to equipment which was regular for these wards. Disconnecting times differ from average 15 seconds for a Dialysis patient, to 89 second for a patient on an Intensive Care ward.

With an interactive design tool, the actual risk and Required Safe Egress Time calculations can be defined. A relative probability calculation indicates the risk on casualties per ward, compared with a design fulfilling the maximum restrictions of the Dutch Building Decree. Together with the gathered data, specific RSET calculations have been made for different types of wards. A comparison can be made between the actual risks on casualties per ward, and the RSET. With these guidelines a better implemented strategy can be incorporated in an early phase of the design process.

Designs for hospital should be focussed more on the required safe egress time of a ward and the actual risks, instead of focusing on square meters. Layouts can be designed with fewer restrictions, but consider actual use, presence of trained staff and validated specific egress times for different types of patients. With the developed design tool which can be used by designers at an early design stage, a more integrated fire safety concept can be incorporated in the design.

Preface

With this thesis I finish my master Building Technology at the Delft University of Technology. During the first part of the master, I developed a growing interest for fire safety engineering, what is an important part of the building industry. With this graduation research I wanted to develop my knowledge about fire safety engineering. With gathering missing data of evacuating specific hospital patients, I was able to develop a design tool to calculate actual risks and specific egress times for specific types of hospital wards.

First of all, I want to thank my mentors of the Delft University of Technology for their guidance during the graduation project. My first mentor Peter van den Engel, who helped me focussing on the achievable experiments and research results. I like to thank my second mentor Frank Schnater for his help in the designing process, and his support in the analysis and interpretation of the results.

Special thanks to Björn Peters. He gave me the opportunity to work on this topic and the possibility to carry out my research at DGMR in The Hague. His expertise and knowledge in the field of fire safety engineering, and particular in hospitals, helped me a enormous to perform my graduation research. I also would like to thank the people working at DGMR in the fire safety engineering. They were always enthusiastic to give me advice or assistance with all different things during my graduation period.

I want to thank the hospitals where I could perform the experiments. Currently, there was not much data available of egress times of hospital wards, and there was no data available of the specific uncoupling and disconnecting times of different types of patients. The experiments gave me the opportunity to add this data to the knowledge of fire safety engineering. I want to thank Harry Lip and Pieter Tramper in particular. Both as head of the in-house emergency service of the hospitals, gave me more insights in how hospitals approach the different issues of fire safety and evacuation procedures in hospitals, and helped me with performing the experiments. I would like to thank all staff of the hospitals who participated in the experiments for their cooperation. Without the hospitals, the research wouldn’t have been possible.

Finally, I would like to thank my family, friends and girlfriend for their support and contribution during my graduation period. Their assistance and thoughts helped me a lot during the process.

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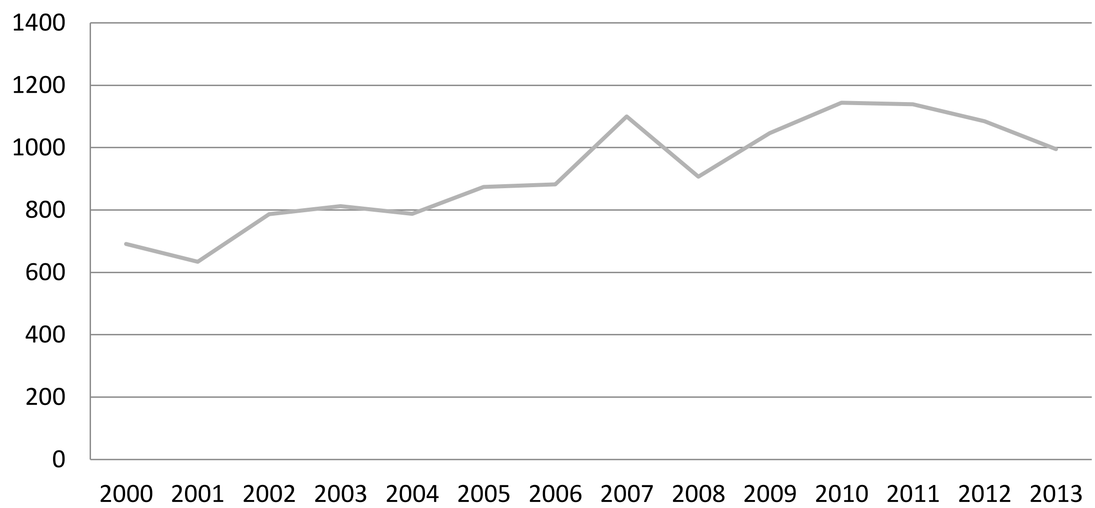
1. INTRODUCTION

Impact and damage of fires

Hospitals are spaces for care and rehabilitation. They often provide different levels of patient support. It is important that there is a safe environment for the (vulnerable) patients and the employees that work in the hospital. However there are risk factors related to the building that can be a threat to the safety of the patients and employees, like a fire in the building.

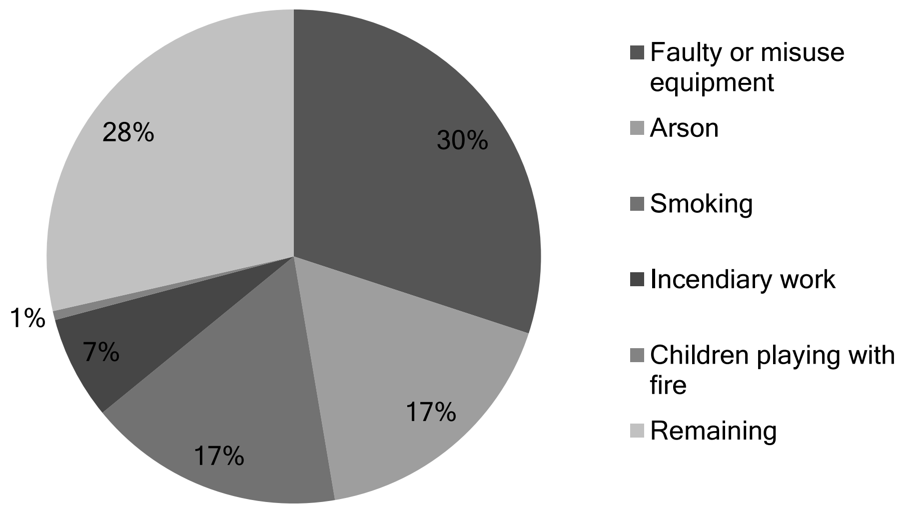
A starting fire produces heat and smoke. It is the smoke that is the greatest threat for people, because the smoke contains different toxic gases. People can only be exposed to smoke for a limited amount of time before it becomes detrimental to health/breathing. When a starting fire can't be extinguished quickly, people need to be evacuated first out of the fire compartment where the fire occurs. When a fire becomes completely uncontrollable not only the fire compartment with the fire but also other parts of the building, if not the entire building, would need evacuation. The damage by heat and smoke generated by a fire can be a problem in the continuity of hospital processes, which can lead to serious financial consequences.

In 2013 there were 1000 indoor fire accidents in Dutch health care premises. As can be seen in graph 1.1. this number is rising since 2000.



Graph 1.1 Indoor fires in Dutch healthcare premises (CBS, 2014).

Faulty or misuse of the equipment is the most important cause (30%) of indoor fires in Dutch healthcare premises. Next to that arson (28%), smoking (17%) and incendiary work (17%) are also main causes of fire. This data is reflecting the cause of fire in Dutch healthcare premises and is not analysed per health care institution. Therefore, the exact causes of fire in hospitals are not known. If the graph only would have been made from data of hospitals, it would probably be different. It can be assumed that for example smoking is not such a high risk in Dutch hospitals, because in all hospital it is forbidden to smoke. A cause that will be more common in hospitals is, for example, spontaneous combustion of equipment. Faulty equipment or misuse of equipment and incendiary work will also be common causes of indoor fires in hospitals.



Graph 1.2 Cause of indoor fires in Dutch healthcare premises, average from 2004 to 2013 (CBS, 2014).

The safety of the patients and the employees in the hospital is the most important. Therefore, the incident of a fire and the fire risk need to be as low as possible. In 2010 there were 263 fires with damage in Dutch health care premises with a total cost of 859.000 euro. In table 1.1. the total costs from 2002-2010 are depicted.

Year	Total fires with damage	Total cost in € (x 1000)
2002	401	8401
2003	382	4210
2004	376	3816
2005	422	6848
2006	357	6199
2007	417	84797
2008	375	18450
2009	344	1753
2010	263	859

Table 1.1 Damage of indoor fires in Dutch healthcare premises (CBS, 2011).

As can be seen in table 1.1 the total costs in 2007 were exceptionally high since there was a fire in the operating theatres of the VUMC in Amsterdam. The fire started because of a short circuit in a refrigerator in an intermediate space. It occurred on a Saturday morning at 6 am, the operating theatres were not in use, so no patients had to be evacuate quickly. But the damage to the operating theatres and the equipment was approximately 50 million euro (VUMC, 2007).

For an integrated fire safety concept, it is important that there is quick fire detection, trained staff who are aware of the risks and have the know how to act and make decisions quickly. The concept must also incorporate well designed fire compartmentation so that a fire can be contained within the fire compartment, (vulnerable) patients can be evacuated across the building first (horizontally), then if necessary down the staircases and/or elevators (vertically), and out of the building. Fire retardant inventory and regular maintenance of equipment can further reduce the risk of fire.

Problem statement

An integrated (fire)safe environment must be part of complete healthcare.

Design trends for hospitals are always changing, currently shifting towards concepts like "healing environment". The main concern of fire safety in hospitals is that there is no complete insight in the real egress time of patients, especially of vulnerable and bedridden patients. Data of egress times is not categorised, and the data is not complete. The current Dutch regulations (based on research done in 1994 and before and common knowledge and assumptions) are still based on old principles of healthcare. These regulations are based on larger patient rooms (6 patients per room for a standard ward) and corridors that are only used as traffic space. In this 'old' concept corridors are considered safe for egress. However, the design tendency is shifting towards smaller individual patient rooms and more spacious corridors with more functions. They serve more as a living room for patients, a place to store equipment and possibilities to charge electrical devices. With this tendency, higher fire risks are introduced within these corridors, possibly leading to less available safe egress time.

Due to budget restrictions, there is limited availability of staff. Especially during night time or weekends. The available staff must unplug and unlock the beds in case of an evacuation. In hospitals, the patient population for the different wards is changing as well. Complex patients are transferred faster to more regular wards, and therefore more equipment must be disconnected to prepare them for evacuation. Because of the complexity more patients are bedridden and are totally dependent on the available staff during an emergency. A reduced availability of staff and increase in more severe patients will lead to more required safe egress time.

There are no design guidelines that can help architects at an early design stage, to create a more integrated fire safety concept. With these guidelines, the safety of (bedridden and vulnerable) patients could be significantly increased.

Objectives

The objectives of the research are;

Categorise data from egress times for different types of patients, including unplugging and unlocking of beds and disconnecting patients from the equipment they are connected to.

Add missing data about egress times, by performing experiments where beds need to be evacuated out of a room, in cooperation with different hospitals in the Netherlands.

Develop a design tool that helps designers with solutions and possibilities for new designs for current, future hospitals and hospitals that are refurbished to raise awareness of fire risks. Verify these design proposals with calculations to determine the effect on decreasing these risks using the gained knowledge about egress times.

Answering the question whether the outdated fire safety requirements of the current Dutch Building decree should be altered and if so, how they should be altered to make current and future hospitals sufficiently safe.

Research aim

The posed objectives lead to the following design brief;

Design guidelines for a state of the art fire safety concept in hospitals that matches new design trends, actual use and corresponding egress times for different groups of (vulnerable) patients.

The design guidelines will show examples of plans with layouts of different hospital wards, taking the available staff into account so that the total evacuation time of ward within the plan can be determined. The fire safety concept will include the limitation of fire and smoke spread, because of the compartment size suggested in the design guidelines.

The influence of new design trends will be further analysed in the research. The safety level of the fire safety concept highly depends on the availability of staff and the type of patients for each different ward. This is important for the egress times, because of the uncoupling and unlocking of equipment patients are connected to. Vulnerable patients are not capable of evacuating on their own either due to their physical condition or because they are bedridden and connected to different kinds of equipment.

Research questions

Problem

What are the current regulations in the Netherlands regarding the fire safety of hospitals?

What are the differences in regulations between the Netherlands and countries with similar healthcare facilities?

What are the current design trends for hospitals?

What design trends have a direct effect on fire safety?

What are the causes of actual fires in hospitals and what was the impact and damage?

What evacuation choices have been made during actual fires in hospitals?

Research

What are the categories and types of wards in existing hospitals?

Can a spectrum of vulnerability of patients in a hospital be defined?

What are the different types of equipment that a patient is connected to?

What are the egress times of different groups of patients, including unplugging and unlocking of equipment?

Do physical conditions (for example obesity) of a patient affect egress times?

Design

What egress times can be defined and categorised by research and experiments?

What number of staff members is necessary in leading/organising the operation of evacuating a hospital? (especially during night times or weekends)

What are the consequences of these egress times for the design?

Are there architectural precedents that demonstrate safe and efficient evacuation of hospitals? (partly based on analysis of existing hospitals)

What visual design proposals can be derived for a fire safety concept that contributes to safer use of hospitals?

Main research question

What design guidelines can be derived for a fire safety concept in hospitals that matches new design trends, actual use and corresponding egress times of vulnerable patients?

2. RESEARCH APPROACH

Objectives

The main objective of the research is to create design guidelines for layouts with an integrated fire safety concept of hospital wards, floors and entire hospitals.

As shown in figure 2.1 the problem is determined. First by the relevance of the current state of hospitals, actual cases of fires on healthcare premises, design trends for new hospitals and the outdated regulations. Research will be carried out for existing egress data of patients in hospitals. Data is already available for disconnecting regular equipment and evacuating patients, both for larger patient rooms as for individual patient rooms. This research is performed by DGMR. Previous papers and research also outline egress times of Intensive Care Units and operating theatres. They also indicate variables that have an impact on the length of time required for evacuation.

New experiments will be performed during the research that primarily focus on hospital wards for which no egress data are available. For example, this will most likely be a neonatal ICU or other hospital wards in which patients are connected to equipment that may prolong the evacuation period. If there is data about (almost) all different types of hospital wards, where (vulnerable) patients are present, a complete evacuation strategy for all types of hospital wards can be designed, making an integrated fire safety concept for complete hospitals possible.

With the design proposals validated by the collected data a better insight is created into how hospital wards can be improved with a well-designed and integrated fire safety concept. This concept will inevitably seek to reduce risk and casualties.

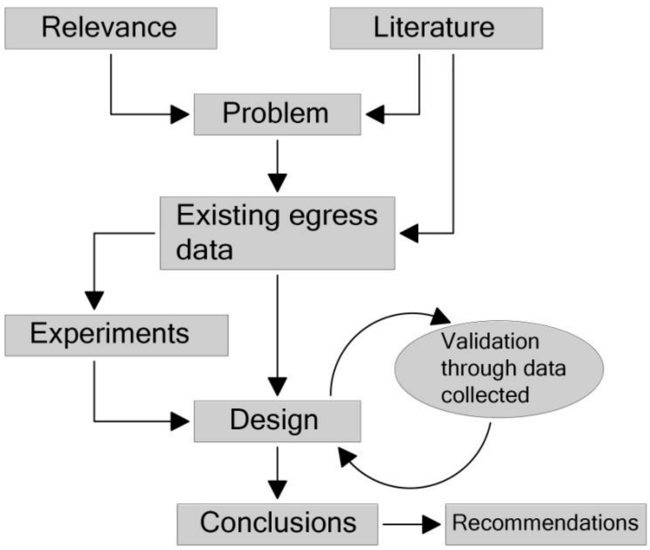


Figure 2.1 Layout of research approach.

Methods

The most important part of the research is gathering the data of egress times for different types of patients. These data will partly be gathered from different research and papers, and results of earlier performed fire drills in hospitals. To make sure that there is sufficient data available to create a design approach suitable for various hospital wards, experiments will be carried out in wards where currently no egress data are available. During an experiments the times as shown in figure 2.2 will be recorded. Experiments will be carried out in cooperation with hospitals All participants during the timed fire drills must fill in a survey, to determine their experience in performing fire drills. All experiments will be carried out several times, to get reliable average values for the times and speeds mentioned in figure 2.2. Times will be recorded by camera's filming on certain places, to avoid that the staff is affected. The effect of fatigue of staff after several rehearsals or the effect of staff interfering with each other while evacuating patients can be interesting for the design strategies of hospital wards.

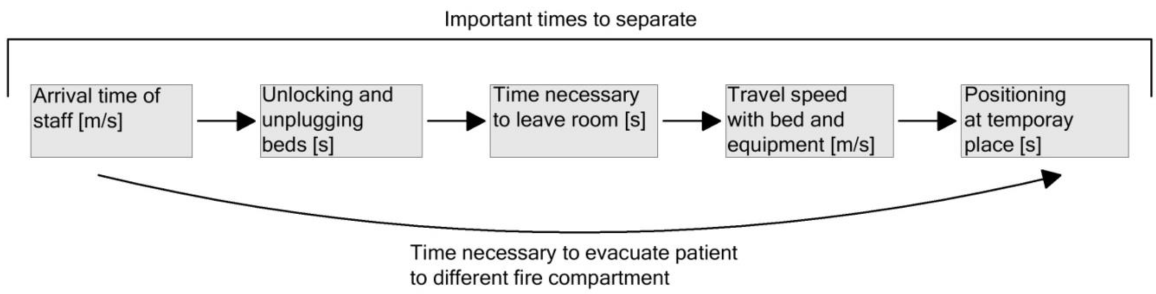


Figure 2.2 Desired times as outcome of experiments.

With these gathered total egress times, times for specific actions and travel speeds, calculations can be made of the egress time of a hospital ward. A combination of the proposed layout and the occupation of staff, a total egress time of the hospital ward can be determined. If this total egress time is not sufficient, proposals can be made to make the layout of the hospital wards more fire safe. An analysis of layouts can be made from current and planned hospitals, and general layouts could be used for future hospitals.

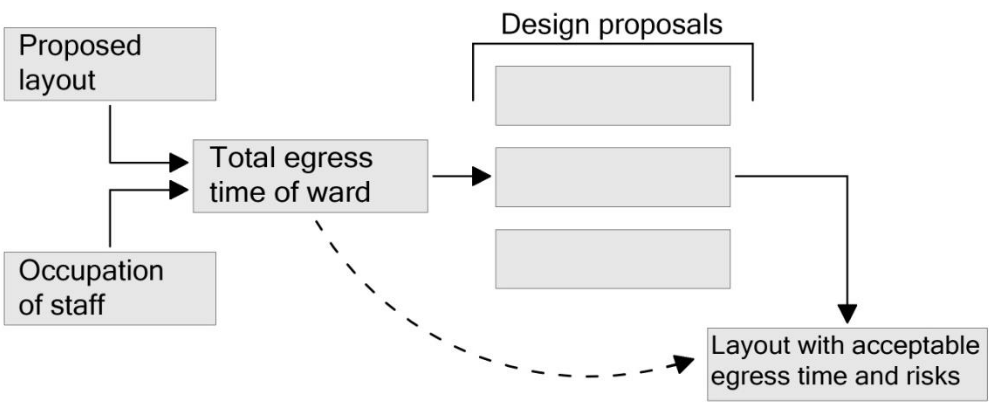


Figure 2.3 Scheme of design proposals.

3. CONTEXT

A fire in a hospital can be caused by various reasons. High risks are for example the flammability of equipment and mattresses. In fire cases the cause of the fire is further described. The cases show how a fire can occur and what the effects of the fires were.

Fire development

A fire in a hospital can develop fast, because of the presence of flammable materials and different types of flammable gases. Important is the difference between the Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET).

There are a lot of variables to determine the development of fires in hospitals. A flame-retardant mattress can for example still burn, if different types of sheets and blankets that are flammable are used. The distribution of oxygen to the fire is a variable that makes a big difference in the fire development. This can be by an open door or window, but also by oxygen that can escape through malfunctioning medical equipment.

To give a better prediction about the fire development, and the probabilities in the scenario of a developing fire, it is important to use an average fire growth for a patient room, adjacent room and corridor. Hence this is an average fire growth, and will not give much information about a real fire that can occur. But it can give an indication about the speed smoke will develop and when a room or a corridor will be filled with smoke, and cannot be used anymore for safe evacuation.

Because of the many variables which have an influence on the development of different types of fire, it is hard to predict the Available Safe Egress Time. It is difficult to do predictions if it’s possible to evacuate people out of a burning room, considering the type and development of fire and the arrival time of staff after they are alarmed. The research will be focused on the RSET of vulnerable patients, and the ability to bring them as quickly as possible to an adjacent smoke and fire compartment, or even more than one fire compartment away from the fire.

Cases of fire on health care premises

To describe the relevance of the need to have a good integrated fire safety concept for hospitals, research has been conducted in cases of fire on healthcare premises on different wards, to describe the relevance and necessity for well-designed integral fire safety concepts in hospitals. These cases demonstrate the urgency needed in evacuation and the extended time taken to evacuate patients, which in some cases were not successful.

Twenteborg hospital in Almelo, the Netherlands

A serious fire occurred in an operating theatre on 28 September 2006 at the Twenteborg hospital in Almelo, the Netherlands. The fire claimed the life of the patient who was undergoing surgery in the operating theatre 8. The Dutch Healthcare Inspectorate has performed research into the causes as a direct consequence of the fire.

The fire started in an anaesthesia machine present in the operating theatre. The equipment was poorly maintained and this may have been the direct cause for the fire. The machine is connected to an oxygen supply that fuelled the fire, allowing it to develop rapidly. The fire was generating a lot of heat and ignited the plastic components of the machine and other equipment. This caused the fast production of a lot of smoke.

Because of the fast development of the fire, the medical team present in the operating theatre was unable to move the patient, who was fixed to a bed. The team tried to extinguish the fire, whilst an employee who had experience as a volunteer firefighter from an adjacent operating theatre decided to close the door to make sure the smoke could not disperse quickly.

The evacuation of the other operating theatres was successful. A fire door between operating theatre 7 and 8 was closed. Room 1 till 7 could evacuate without problems. But operating theatres 9 till 12 encountered problems. The escape route clearly marked let to an exterior staircase, where bedridden patients could not be evacuated, and had to be removed by firefighters. The plan shows the evacuation of a bedridden patient from operating theatre 9. It was difficult to find a passage through the rooms to the other corridor. If the other fire door would also close automatically, it would be impossible to evacuate bedridden patients. This situation is far from unusual and in accordance with the current fire regulations.

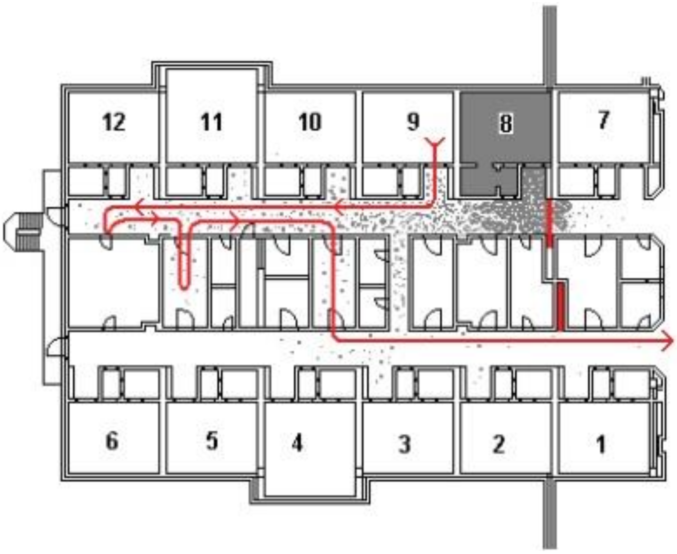


Figure 3.1 Plan of operating theatres. Shown is the evacuation route of the patient from operating theatre 9 (Dutch Healthcare Inspectorate, 2008).

Private hospital in Hamilton, New Zealand

On the 6th of September 2008, a fire occurred in a private hospital in Hamilton, New Zealand. The fire was small and mostly only smouldering, and occurred in the plant room above an operating theatre. Research and re-enactment have been performed to analyse the incident and the effects for patient and staff (Scott, 2009).

The hospital has an operating sprinkler system and smoke detection system present. Despite the smoke accumulating in the plant room, and smoke entering the operating theatre, the detectors were not triggered. The fire was only smouldering and creating a lot of smoke, but the fire did not get hot enough to activate the sprinkler system. The smoke detection was not triggered because of the air conditioning flows of the operating theatre. The smoke was drawn away from the detectors to the ducts, allowing the smoke to enter the operating theatre.

During the re-enactment of the incident the medical team present in the operating theatre was not aware of the smoke entering to room, probably because of the dimmed lights. The use of surgical masks prevented the team to easily smell the smoke. A surgeon entering the room smelt the smoke and made the team that was present in the room aware. The surgeon decides to stop the operation and prepare the patient (which during the trial was a dummy) for evacuation. Unless a simple operation was simulated, it took almost ten minutes to prepare for evacuation. Because of this long evacuation time to be able to evacuate the patient out of the room, operating theatres could be designed as a separate fire compartment where a longer stay during a fire is possible. This requires more attention when developing fire safety concepts for hospitals.

Federico II university hospital in Naples, Italy

The next case that will be discussed is an evacuation of an Intensive Care Unit of the Federico II university hospital in Naples, Italy (Rispoli et all., 2014). At 17:30 on December 17th 2010 nine patients were in the Intensive Care Unit, when medical equipment alarms sounded, because of a lack of power supply. The staff, consisting of 11 members in total, checked the operation of equipment. During the check the fire alarm was activated because smoke reached different parts of the hospital floor where the Intensive Care Unit was located. The Intensive Care Unit was separated from the other parts of the floor by a fire door.

The cause of the fire was in the uninterruptible power supply, placed in the basement. Smoke entered other parts of the hospital. Because of the smoke and the lack of power for the medical equipment there was a direct need to evacuate the patients from the Intensive Care Unit to other wards in the hospital or to a nearby hospital, where there was room for five additional patients on the Intensive Care Unit. The importance for fast evacuation was not only because of the potential fire, but the batteries of the mechanical aspiration had an average duration of 30 minutes. If mechanical aspiration would stop working, staff would directly need to switch to manual ventilation.

Despite this, no patients were harmed during the evacuation, but it did expose certain problems. The fire door didn't stop the smoke entirely in entering the Intensive Care Unit. Patients were not exposed to this smoke because the ventilators had filters, but staff members experienced irritation. After the incident, an extra door was placed between the basement and the central stair case. This extra door will ensure that smoke can't easily enter the remaining part of the hospital. The evacuation of each patient from the Intensive Care to an ambulance took an average of seven minutes.

Rivierduinen psychiatric institution Oegstgeest, the Netherlands

Although the fire in Oegstgeest was in the psychiatric institution Rivierduinen, and not in a hospital, the case gives an example of an evacuation with reduced self-reliant patients, which were not bedridden.

On Saturday night March 12th 2011, a fire detector is activated by a small fire starting from the mattress of a patient room. Present staff, consisting of two trained responders, discover the fire fast, but it takes time to evacuate the patient out of the room. Because of problems with the extinguisher staff is not able to extinguish the starting fire. They decide to evacuate all patients out of the building.

The fire develops fast because the burning mattress is not fire retardant. The staff member forgot to close the door to the room, which fed the fire with oxygen resulting in smoke spreading quickly. The staff experience problems in evacuating the patients. They don't want to leave their room or are hiding themselves. When the fire brigade arrives after ten minutes, there are still five patients present in the building. This results in two casualties, three are rescued from the building and one of them dies later in the hospital.

In a research done by the Dutch Safety Board a few conclusions are made (Dutch Safety Board, 2012). The psychiatric institution met all requirements for fire safety, as they are applied in the Dutch regulations. But coherent decisions about the building, the inventory and preparation of staff for emergency situations are necessary. The regulations are not specific enough regarding the self-capability of patients. An integrated approach could have made a difference in this case.

Figure 3.2 Visualization of psychiatric institution. Shown is the development of the fire and smoke spreading out of the patient room (Dutch Safety Board, 2012).

Regulations

To get a clear view of the current regulations for hospitals, a study has been conducted on the various requirements for fire safety in the Netherlands. This is compared to countries with similar healthcare facilities.

Dutch Building Decree

Evacuation and fire compartments are an important part of the Dutch Building Decree. Special requirements are made for evacuation routes and fire compartments. These regulations are defined in the Dutch Building Decree 2012. The requirements for compartment sizes and escape routes are outlined on the following pages.

Compartmentation and escape routes

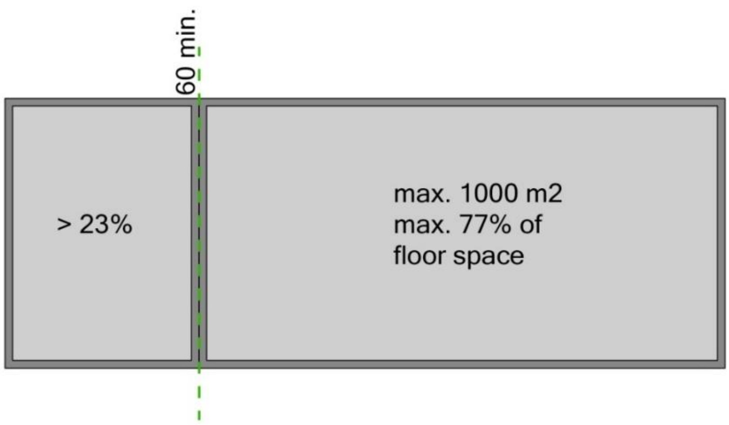


Figure 3.3 Size of fire compartments.

In a healthcare building, such as a hospital, a fire compartment is maximum 1000 m2 and has a maximum floor space of 77% per floor, to be able to evacuate patients during the first stage of horizontal evacuation on the same floor. The resistance to fire penetration and spread (WBDBO) must be at least 60 minutes between fire compartments.

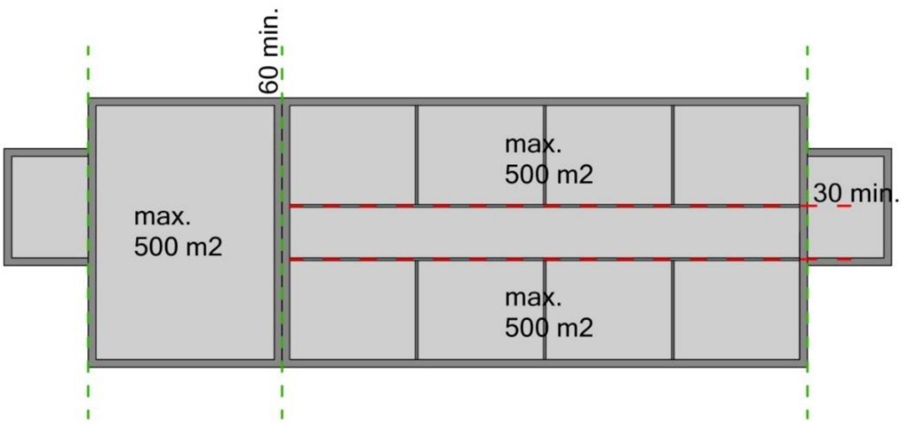


Figure 3.4 Size of sub fire compartments in healthcare.

A fire compartment must be derived in sub fire compartments. In healthcare facilities the maximum size of a sub fire compartment is 500 m2. The WBDBO between sub fire compartments must be at least 30 minutes.

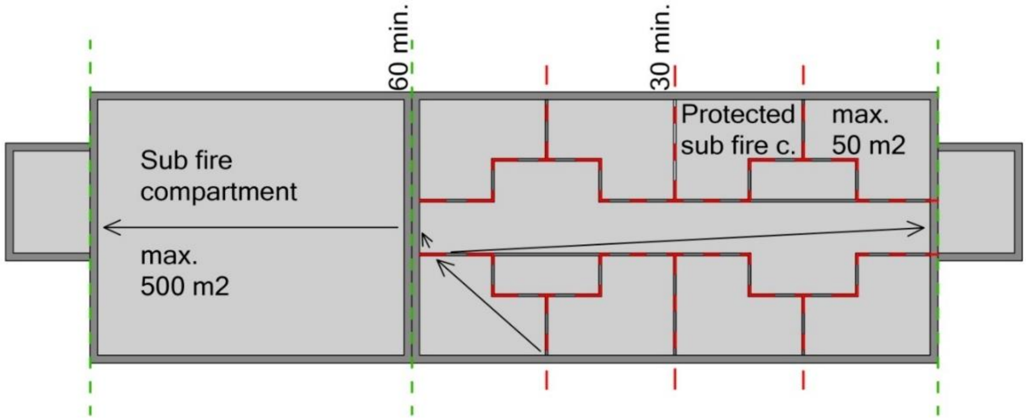


Figure 3.5 Layout of protected sub fire compartments.

Sub fire compartments need to be protected sub fire compartments if there is a sleeping area. Patient rooms are an example of sleeping areas as there are beds inside the room. If patients are bedridden, the surveillance level determines the size of a protected sub fire compartment. If there is continuous surveillance, such as an Intensive Care Unit, the size of a protected sub fire compartment can be a maximum 500 m2. If there is no continuous surveillance, such as in a patient room, a protected sub fire compartment can be a maximum of 50 m2. Only related rooms of the sleeping area can be in the same protected sub fire compartment.

Other functions, such as a linen room or a nurse station can be connected to the escape route, without any further requirements for the fire resistance. The escape route to a different fire compartment has a maximum length of 30 meters.

If there is no second escape route out of a fire compartment, an escape route to a staircase, allowing a patient to leave the floor, must be made extra safe. This is a so called extra protected escape route. This escape route must have walls with a WBDBO of at least 60 minutes, and has a maximum length of 30 meters. If more than 37 people have to use the escape route to leave a sub fire compartment, it must always be an extra protected escape route.

Regulations in countries with comparable health care facilities

To get a clear view on the state of the Dutch regulations, similar healthcare regulations from other countries have been used for comparison. Behaviour of materials is determined in the EU in standardised fire classes, but the application between the countries of the EU is different. There are also differences in the length of escape routes and the maximum size of fire compartments.

An overview of the current regulations which are applied, is found in a comparison of national fire regulations in EU for three different buildings (Albiac, Hughes, & Messerschmidt, 2016).

	The Netherlands	Belgium	Sweden	Germany	England	Slovakia
Maximum length to escape route in sleeping area[m1]	30 m	30 m (15 m if single route)	30 m	35 m (10 m if single route)	30 m (15 m if single route)	3,3 minutes (2 minutes if single route)
Maximum size of fire compartment [m2]	1000 m2	2500 m2	Each care unit or operating theatre	Every floor divided into two compartments	2000 m2	-
Maximum size of protected sub fire compartment (patient room) [m2]	50 m2 (500 m2 with permanent surveillance)	-	-	Fire wall every 40 m	750	-
Requirements for sprinklers	None	Only with cooking appliances	Yes, unless extra staff is available to proceed evacuation.	Alternative for sub fire compartments	Yes	Yes
Requirements for materials in escape route	B-s2, d2	A1, A2	B-s1, d0	A1, A2	B s3, d2	-

Table 3.1 Regulations comparison between the Netherlands and similar countries.

Belgium

The Belgium regulations for fire safety are determined in the KB hospitals 1979. The maximum length from an exit of a patient room to a staircase can be 30 meters. Escape routes can be longer if there is a separation by a fire resisting wall and self-closing fire resisting doors every 30 meters. These walls and doors must have a flame resistance of at least 30 minutes. An escape route with a dead end, is maximum 15 meters. Interior walls in escape routes must have a fire resistance of 60 minutes, doors in escape routes must have a fire resistance of 30 minutes.

A fire compartment must be smaller than 2500 square meters. A compartment must be in direct horizontal connection with another compartment on the same floor. This compartment must be able to hold all patients and other staff or visitors from the other compartment. There are no further requirements for sub fire compartments. An automatic extinguish installation must be installed at cooking appliances.

Sweden

Sweden regulations require every care unit or operating theatre to be a separate fire compartment, but there are no further restrictions on the maximum number of people in these compartments. The maximum distance to escape routes is 30 meter.
Restrictions on furniture in communal areas are given by a maximum allowed fire load of 360 MJ/m2.

Germany

German regulations require in general an automatic fire-extinguishing system. Every floor must be at least a fire compartment, where each care unit is divided into a minimum of two compartments. Every compartment must be able to hold all people of the nearest and largest fire compartment.

The maximum distance of escape is 35 meters. If only a single direction of escape is possible, the maximum distance is 10 meters.

England

In England, the regulations divide the hospital in different parts. A floor must be divided in compartments, sub compartments and so called hospital streets, what can be compared with extra protected escape routes in the Dutch regulations.

Floors up to 12m above ground level with an area less than 1000 m2 should be divided into a minimum of two compartments if they contain maximum 30. Floors up to 12m above ground level with an area more than 1000 m2 should be divided in at least 3 compartments. Sub compartments have to be enclosed by walls having a fire resistance of 30 minutes minimum.

The maximum distance to another compartment is 60 meter, from every point in a compartment. The maximum distance in a sub compartment is 30 meter to an exit. This can be another compartment, protected escape route or a stairway which lead to a final exit. The maximum length before there is a choice of escape routes should be no more than 15 meters.

If there is treatment of very high dependency patients on upper floors, at least two escape lifts should be provided. Both should be sufficiently remote from each other, to ensure at least one is available. But escape stairways are always required. The width of escape stairs must be determined by the mattress manoeuvrability, to be able to evacuate patients on mattresses.

Slovakia

Egress times in healthcare premises in Slovakia are determined differently than in other countries in the EU. In Slovakia the maximum allowable distances are based on different times. In unprotected evacuation routes the maximum allowable evacuation time is 2 minutes if one direction is applicable, 3,3 minutes if evacuation is possible in two directions or more. If there is a partially protected evacuation route, one direction the maximum allowable evacuation time is 3 – 4 minutes and 4 – 6 minutes if there are two directions or more. If the evacuation route is fully protected, 6 – 30 minutes for single route and 10 – 30 minutes for 2 or more directions is applicable.

United States

In the United States strict regulations for sprinklers are applied. Since 2009 the regulations require automatic sprinkler protection in all new health care premises and many existing ones. It is stated that sprinkles are considered as the most effective fire protection for health care facilities.

New design trends

The design approach of hospitals is constantly changing and developing. Hospitals are complex buildings, design briefs are extensive. Many processes need to be integrated sufficiently into a hospital building to create a convenient working place for staff and healing place for patients.

Healing environment

Almost all recently designed hospitals have been designed in accordance to the healing environment. The aim of a healing environment is clear, namely creating an environment which helps patients to recover. Stress reduction is an important part of a healing environment. The architecture of a building is a big part of the healing environment, and may help patients to recover (Mens, N., Wagenaar C., 2009).

An important strategy of the healing environment is to promote single patient rooms. The necessity of these rooms has various reasons. The main reason for single person rooms are that the patient has more privacy, and the patients sleep will probably improve, since there are no other patients to disturb their night’s rest. The risk of infections in a single patient room is reduced. In single person rooms, more accommodation is available for visitors of the patient. Including possibilities for visitors to stay the night in the patient room, the so-called rooming in. Especially for patients who are in a certain state of confusion, rooming in can provide reassurance.

Figure 3.6 Single patient room and communal space Sittard-Geleen hospital (Bonnema architects).

Extra functions are added to the corridor where the patient’s rooms are connected. This is to maintain social interaction, since patients are individually in their room. The corridor encourages patients to leave their rooms and go out, stimulating the patient’s recovery process. But in this concept the corridor changes from a space safe for egress to more of a living room with additional functions and corresponding fire risks.

Figure 3.7 Single patient room and communal space Amersfoort hospital (Atelier Pro).

Another strategy to improve fire safety is to make the hospitals layout more coherent and navigable. Through architectural design a large hospital building can be separated into several buildings. With atria, a better orientation inside a building can be created. Visitors can more easily find the right destination in the hospital. In case of emergency however, these atria can cause several problems.

In the atria, several extra functions can be added such as restaurant, front desks and waiting areas. These functions potentially have higher fire risks. If a fire occurs, the atrium can fill with smoke. A SHEVS (Smoke and Heat Exhaust Ventilation System) can help exhaust smoke but a certain amount of smoke will always be present if a fire occurs.

The atria are designed to give people a better orientation, and help people get to the right destination within the hospital. Because people tend to choose the same way to evacuate a building as they entered the building, people will try to evacuate through the atrium. With the presence of smoke in the atrium, this can lead to disorientation when people need to evacuate through a different route. If despite the smoke, they choose to evacuate through the atrium, people may suffer smoke damage or will not be able to leave the smoke-filled atrium.

Figure 3.8 Atrium in Delft hospital (EGM architects)

With these changing design trends, some fire safety risks are increased. If patients must be evacuated, walking distances for staff members are longer if patients are in single person rooms, instead of multiple patient rooms. This influences the total evacuation time of a hospital ward. However, when a fire occurs in a patient room, fewer patients are directly exposed to the fire.

Important observations

Research into fire cases, the current state of regulations and the current design trends lead to important observations which influence the fire safety and can be used during the design phase.

- Actual fire cases showed that when a fire occur in different health care institutes, the fire can develop fast and it leads to problems during evacuation. Building layouts, evacuation procedures and the knowledge of staff about these procedures don't' seems to cover the most important risks. This can have major consequences when a fire occurs.

- Different functions are also added to corridors with patient rooms, such as linen rooms, equipment and bed storage and nurse stations. These functions also have differing fire risks and potential fire growth. Adding these functions, directly in or in open connection with the same corridor as the patient rooms, can introduce new scenarios in which the corridor could fill quickly with smoke when a fire occurs. Figure 3.9 shows a scenario when a fire occurs in a nurse station, where all patients room are threatened simultaneously. If this happens it is difficult or impossible for staff to evacuate patients out of their rooms to an adjacent fire compartment.

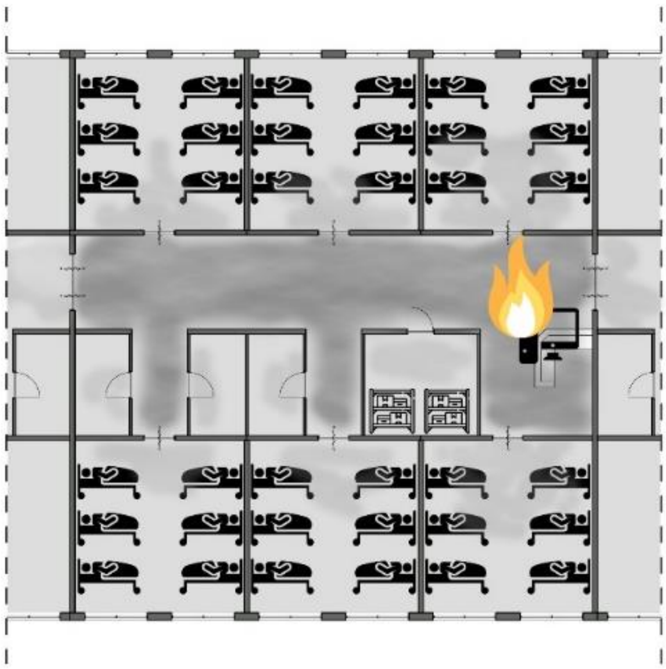


Figure 3.9 Layout of hospital ward in accordance with current regulations

- Regulations are focused on compartment size and maximum allowable evacuation routes lengths. In the Netherlands and countries with similar health care systems these compartment size is focussed on square meters and linear meters for evacuation routes. Compartment sizes can be large, and therefore be difficult to evacuate by a small number of staff members in a safe timespan if a fire occurs.

- In regulations no distinction is made in different required evacuation times per patient on different types of wards. All wards and parts of hospitals can be designed with the same restrictions. There is no knowledge about the actual egress times per specific patient.

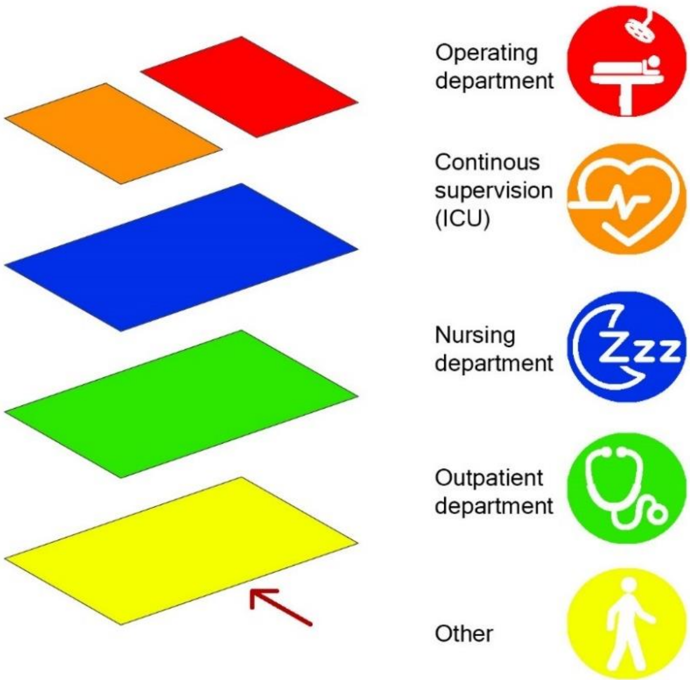


Figure 3.10 Typical composition of hospital

- A trend in the designs of both older hospitals and more recent designed hospitals is the Outpatients departments closer to the entrance and nursing departments and other intensive care further away from the entrance, as showed in the figure above. The strategy behind this is that hospitals try to place the nursing departments in calmer parts of the hospital. This has the direct consequence that it can be that the nursing departments, intensive care and the operating theatres are on the higher floors of a hospital. But these wards have the most vulnerable patients in case of evacuation. Analysis of the composition of hospitals for both older and recent designed hospitals are added in the appendix.

- Corridors with only stairs on one end of the corridor can create problems if an evacuation of bedridden people is necessary. When the exit to the different parts of the hospital with elevators is blocked, the only option left is to use the stairs. This can lead to undesirable consequences when vulnerable patients must be transported on an uncomfortable assist device via stairs, or even via exterior staircases.

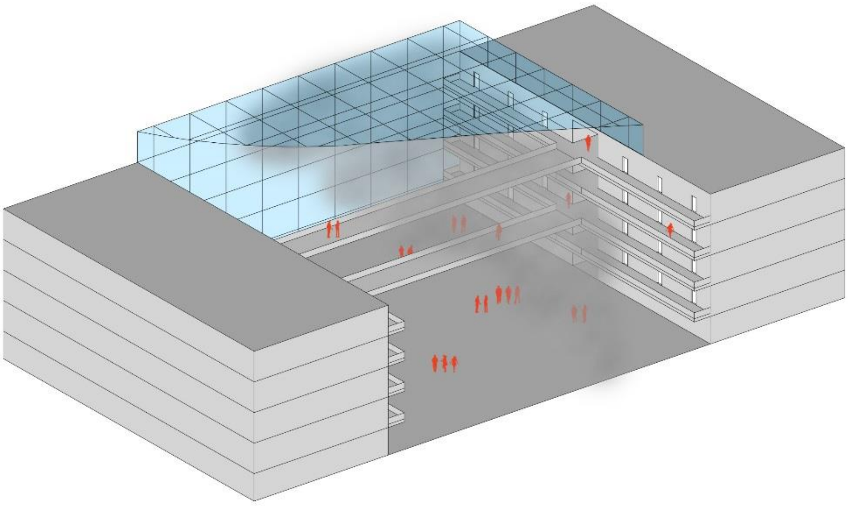


Figure 3.11 Atrium in hospital

- In the design of new hospitals atria are becoming more common in entrance areas. With atria, hospitals can create easier orientation for visitors. Adding extra functions such as a restaurant to the atrium, enhances the risk of an occurring fire. If a fire occurs in an atrium smoke will easily spread, as shown in the figure above. This will lead to disorientation and possible injury of people.

- In the modern design strategies of hospitals, almost all rooms are made as single patient rooms, following the “healing environment” strategy. Corridors are designed as communal space, where patients can retain social interaction. This kind of use for the corridor as living room changes the function of the corridor from primarily access and egress to a use with more potential fire risks. Also, the furniture creates a higher fire potential.

4. EXISTING EGRESS DATA

There is already data about egress times of vulnerable persons available. Data has been gathered from different scientific papers and existing videos of evacuation drills at specific hospital wards. The data can be used to design fire safety concepts in hospital wards and highlight where additional research data could be added to make a total integrated fire safety concept for both individual wards and entire hospitals possible.

Pre-evacuation

It is important to consider the time people require before starting to evacuate to calculate the total egress time. Research is done into the pre-evacuation time in hospitals (Gwyne, 2003). Data is gathered from the analysis of an evacuation drill where patients and staff were present in different departments and waiting areas. It is important to note that patients only started to evacuate when they were prompted by staff members. The role of staff during an evacuation is vital as patients seems to be dependent on the behaviour of staff members.

	Pre-evacuation time	Number of test persons
Staff	44.1 s.	19
Patients	50.8 s.	14

Table 4.1 Pre-evacuation time during fire drill in a hospital.

Disabled people

In the research the movement speeds of different types of disabled people are analysed (Boyce, Shields, Silcock, 1991). The horizontal speed and the speed on stairs are timed. The speed of different types of wheelchair users are also timed. Almost all values seem to be relevant considering the quantity of test subjects, and gives an indication about the movement speeds of disabled people.

	Horizontal speed	Number of test persons	Speed on stairs (ascent)	Number of test persons
No aid	0.95 m/s.	52	0.36 m/s.	19
Crutches	0.94 m/s.	6	0.22 m/s.	1
Walking stick	0.81 m/s.	33	0.32 m/s.	9
Rollator	0.57 m/s.	10	0.16 m/s.	1
Blind (assisted)	0.78 m/s.	18	0.26 m/s.	3

Table 4.2 Speeds of disabled people horizontal and stairs.

	Horizontal speed	Number of test persons
Manual	0.69 m/s.	12
Electric	0.89 m/s.	2
Manuel (assisted)	1.30 m/s.	16

Table 4.3 Speed of wheelchair users.

Evacuation with wheelchairs can have advantages towards evacuation of patients in bed, because during a large-scale evacuation beds will take up a lot of space in the corridors. Preparation times for people to asses to move to a wheelchair must be considered. In the research performed in several community hospitals the average age of patients was above 60 years or older (MacCallum, 2015). All recorded times were from the point a handler puts a hand on the elderly person until the breaks of the wheelchair have been released.

	Comfortable chair to wheelchair	Toilet to wheelchair	Bed to wheelchair
Elderly person	32.87 s.	39.77 s.	29.09 s.

Table 4.4 Pre-movement times of wheelchair users.

Elderly people

Due to the growing population of elderly people, a research is performed particularly in their movement speeds (Samochin, 2012). Experiments are performed on senior citizen's health care buildings and a total of 883 measurements of travel speeds are made. The results show that the travel speed of elderly people is significantly slower than regular people.

	Horizontal speed	Stairs down
Disabled people without movement aids	0.7 m/s.	0.47 m/s.
Disabled people with one stick or crutch	0.43 m/s.	0.20 m/s.
Mixed flow of elderly people	0.614 m/s.	0.38 m/s.

Table 4.5 Movement speed of elderly people.

Children

The walking speeds of a group of children were measured during a 7-year long experiment to define the changes in movement speed while children are growing up (Stansfield, 2001). In age group 5-6 years the children walked the slowest, at 1.07 m/s. In age group 9-10 children walked the fastest, at 1.36 m/s. The mean value of the movement speed of mobile children shows that it is slightly slower than mobile adults.

	Horizontal speed	Number of trails
Children 5-12 year	1.23 m/s.	1040

Table 4.6 Movement speed of children.

In a series of fire drills at an elementary school, the walking speed of children are captured (Ono, 2012). Evacuation of the children was performed in groups, the speed in the same group differs a lot, mostly because of the pace of the leader and the distance between students in line.

	Horizontal speed	Stairs down	Number of test persons
Children 6-14 year	1.10 m/s.	0.98 m/s.	906

Table 4.7 Movement speed of children.

Operating theatre

As described earlier in chapter three, an analysis of a fire incident in an operating theatre is made to see what the pre-evacuation time, and preparation time is during surgery (Scott, 2009). The incident was later simulated, to derive the evacuation times. Despite the direct need to evacuate because of the presence of smoke, and the assistance of an extra operating team, the evacuation took 9 minutes and 18 seconds. The total staff including eight persons of the both operating teams, plus supporting nurses. The surgery was quite simple, but evacuation already took almost ten minutes. If the surgery was complex, and a safe possible evacuation of the patient is desired, a fire safety concept with long possible evacuation times will be necessary.

Type of ward	Preparation time	Number of staff	Number of tests
Operating theatre	558 s. (9 min, 18 s.)	8+	1

Table 4.8 Preparation time for evacuating an operating theatre.

Movement assist devices

The preparation times and movement speeds of trained staff using movement assist equipment have been measured (Hunt, 2012). The time required to move a person from a wheelchair to a movement device and the number of required operators are shown in the table below. The table also includes the horizontal speed including number of required operators and vertical speed on stairs including number of required operators.

The rescue sheet is the slowest device in transporting an ambulant patient, while the evacuation chair was the fastest on the entire evacuation procedure. However, it takes a lot of time to evacuate people via stairs using movement assist devices.

	Preparation time	Number of operators	Horizontal speed	Number of operators	Speed over the whole stairwell portion	Number of operators
Stretcher	78 s.	2	1.04 m/s.	4	0.53 m/s.	4
Evacuation chair	33 s.	2	1.46 m/s.	1	0.83 m/s.	1
Carry chair	42 s.	2	1.50 m/s.	1	0.58 m/s.	4
Rescue sheet	65 s.	2	0.89 m/s.	2	0.67 m/s.	2

Table 4.9 Important times using movement assist devices.

Bedridden patients

The research is performed by the company DGMR to validate the differences between the egress times of one patient room of six patients, and the egress time of six single patient rooms (Peters, 2007). The current Dutch Building Decree is based on the concept of evacuating a patient room of six patients. But new hospitals are based on new ideas about architecture, and more hospitals are shifting to single patient rooms.

The times that could be derived from the research are shown in the table below. The egress times are the total times per patient. It is possible to evacuate six patients out of one patient room within 2 minutes. To evacuate six patients out of single patient rooms will also take around 2 minutes. In both cases uncoupling is not included. With uncoupling the beds in both cases the total evacuation time will increase to 3 to 3,5 minutes.

	Uncoupling time	Leaving room	Number of operators	Number of tests
One bed out of six patients room without uncoupling	-	12 s.	2	4
One bed out of six patients room with uncoupling	10.4 s.	8.4 s.	2	10
One bed out of single patient room without uncoupling	-	10.94 s.	2	16
One bed out of single patient room with uncoupling	12 s.	8.6 s.	2	5
One bed out of single patient room with uncoupling + oxygen flow meter	15.4	9.6 s.	2	5

Table 4.10 Egress times of different types of patient rooms.

Data about egress times is captured in a research into the evacuation of bedridden building occupants, where data is gathered of bedridden persons in nursing homes and hospitals (Strating, 2013). Many evacuation drills are performed in several hospitals, so it gives a good indication about the total time and the travel speed of an evacuation of a bedridden patient.

In the performed research, some experiments are measured for evacuating patients from an Intensive Care Unit. The tests were repeatedly conducted on two different patients who were connected to different equipment each time. Results show that uncoupling takes a lot of time.

	Uncoupling time	Horizontal speed	Placing time	Number of operators	Number of tests
Patient with uncoupling beds	8.59 s.	0.88 m/s.	8.11 s.	2	91
Intensive care unit	81.89 s.	1.14 m/s.	5.73 s.	2	10

Table 4.11 Egress times of regular patients and ICU patients.

5. EXPERIMENTS

To extend the knowledge about the egress times of vulnerable patients, different types of evacuations (experiments) are performed. Evacuation drills of a hospital ward were recorded, to get more insight in the behaviour of staff and patients, and the time needed for different phases within the evacuation procedure. To get more insight in the egress times of specific patients, also a set of evacuation drills are performed to derive separate egress times of patients per specific ward.

Evacuation drill on regular hospital ward

To get more insight in the behaviour of staff during an evacuation drill and the evacuation times for specific patients, two rounds of evacuation drills were recorded. The drills were performed in an older hospital ward with a traditional layout.

The hospital ward is one fire compartment, and consists out of 6 multiple patient rooms, with a maximum of 4 patients per room. In the ward, there are also 8 single patient rooms. The ward can be accessed from the central core of the hospital, where the elevators are placed. At the entrance of the ward the nurse station is located, which is in open connection with the corridor. Beside the nurse station and the patient rooms, some auxiliary rooms are in the ward. The rooms are used for example as toilets or as storage. The rooms on the ward didn't have self-closing doors. Since the hospital building is older, self-closing doors are not mandatory. At the end of the corridor there is a second evacuation route. This second evacuation route is a staircase, which can be used for bedridden patients using assist devices on the stairs. In this hospital special mattresses are used. Evacuation of patients by using the staircase is not preferred, but when the main evacuation route to the other part of the hospital with the elevators is blocked, using the staircase will be necessary.

The evacuation was performed by 3 staff members per evacuation drill. The level of experience of staff members was between 6 and 24 months employed for the hospital. Not all patient rooms on the ward were used during the evacuation drills. Four multiple patient rooms and four single patient's rooms needed to be evacuated, giving a total of 14 patients. Because of the activated alarm, two extra staff members were automatically called to assist during the evacuation. They helped the staff who was already present with moving beds, and checked at the end of the drill if all patients have been evacuated from the patient rooms.

Patients were connected to several equipment that is standard for regular hospital wards, therefore realistic evacuation times could be gathered. During two evacuation rounds different scenarios were simulated. During the first evacuation drill a fire at the end of the ward close to the stairs was simulated, all patients could be evacuated on the same floor to the central core of the hospital. In the second evacuation drill a fire was simulated close to the entrance from the central core to the ward. Some patients were evacuated to the central core, but some patients had to be evacuated the stairs.

Specific data gathered from the recordings of the evacuation drills are shown in table 5.1 till table 5.4.

	Arrival time [s]	Uncoupling time [s]	Leaving room [s]	Total time [s]	Number of staff members
1	3	9	16	28	1
2	11	12	9	52	1
3	4	30	8	42	1
4	2	16	8	26	1
5	7	52	15	74	1
6	3	14	26	43	1

Table 5.1 Evacuation times regular patient first evacuation drill.

	Arrival time [s]	Uncoupling time [s]	Leaving room [s]	Total time [s]	Number of staff members
1	11	5	23	39	1
2	7	12	16	35	1
3	9	15	8	32	1

Table 5.2 Evacuation times regular patient second evacuation drill.

	Arrival time [s]	Uncoupling time [s]	Leaving room [s]	Total time [s]	Number of staff members
Avg.	8,6	18,3	14,3	41,2	1

Table 5.3 Evacuation times regular patient average.

	Preparing time [s]	Horizontal evacuation [s]	Evacuation time on stairs [s]	Total evacuation time [s]	Number of staff members
1	114	33	60	207	2
2	94	36	61	191	2
Avg.	104	34,5	60,5	199	2

Table 5.4 Evacuating patient from stairs.

Hence the less data gathered during the evacuation drills of evacuating bedridden patients by an evacuation mattress from stairs, the drill showed that evacuating bedridden patients using stairs must be avoided if possible. Only two times it has been recorded that a patient has been evacuated on an evacuation mattress via the stairs. However, the average evacuation time shows that it took more than 3 minutes to evacuate a patient via stairs.

Evacuating of bedridden and vulnerable patients with an assisting device to descend the stairs must be prevented as much as possible. Preparing and transporting the patient takes a lot of time, and patients and staff are in areas where they could be affected by smoke. The evacuation drill showed that staff is not used to handle the assist device to evacuate patients on stairs. Confusion about how to use the mattress takes a lot of time. Beside the time it takes to evacuate vulnerable and bedridden patients down stairs, descending the stairs is very uncomfortable for patients.

Specific hospital wards

To define the egress times for different types of vulnerable patients in hospital wards, experiments are performed. These experiments are performed on multiple wards, to determine the different uncoupling times of multiple patients.

The actual time needed to disconnect these patients from all equipment to prepare them for evacuation have been determined as a part of the total egress time per patient, in which the different phases of that total evacuation have been recorded and analysed. Data about the following patients is gathered:

- Standard patients (for wards such as general surgery);
- Dialysis patients;
- Intensive Care patients;
- Neonatal ICU (incubator) patients;
- Heart monitoring patients;
- Recovery patients.

During the evacuation drills the hospital was in regularly use. Therefore, only one single patient room per ward was used during evacuation. Therefore, the effect of multiple staff members evacuating beds and hindering each other, could not be determined, and is not implied in the results.

On every ward the evacuation drill was performed by five couple's separately. Every couple did an evacuation drill of one patient two times, to be able to determine an average value for evacuating the specific patient. Different staff members did take part in the experiments. During an emergency in a hospital, different determined staff can get a call to come assist for an evacuation. It is interesting to see what the differences are in uncoupling times per ward per patient, but also what the differences are in the evacuation speed between staff with experience working on the ward, or other nursing wards, and staff who are not used to work with patients. Before every experiment staff is asked about their normal function in the hospital. The experience of the staff is displayed in the tables, where '++' is used to work with 'the equipment, the category '+' is used to work on other nursing wards. The last category '-' is not used to work with patient equipment at all.

All staff members who took part in the experiments were trained for evacuation drills, and all did know what the evacuation procedures are in the hospital. During the experiments, all staff members wanted to achieve good and fast results. The approaching speed was fast walking, but they didn't run. The uncoupling of the equipment and moving the bed out of the room was done fast, but carefully. In the corridor staff walked fast with the bed. Staff members could proceed a full evacuation of the ward on this speed.

On every ward the patient used for evacuation was connected to equipment which is standard for this ward. Specialised staff connected the patient to equipment where patients mostly are connected to. Some patient on these types of ward will be connected to more specialised equipment, and some patients on less equipment. But with the equipment used an average value could be determined for the specific wards. For the evacuation rounds no real patients were used, but random persons of a normal weight. During the evacuation drills there was none or less communication between the staff and the patient. The data gathered didn't imply the factor of patients who panicked and could disturb the evacuation procedure.

Dialysis

On the Dialysis ward the patient is connected with two tubes to the dialysis equipment. When the patient needs to be evacuated, the tubes can easily be detached. After detaching the patient can be transported directly, without any further equipment that must be taken. The disconnecting of the tubes should be done by specialised staff, who are used to work with the equipment. During the experiments, all couples were assisted by a staff member who only helped disconnecting.

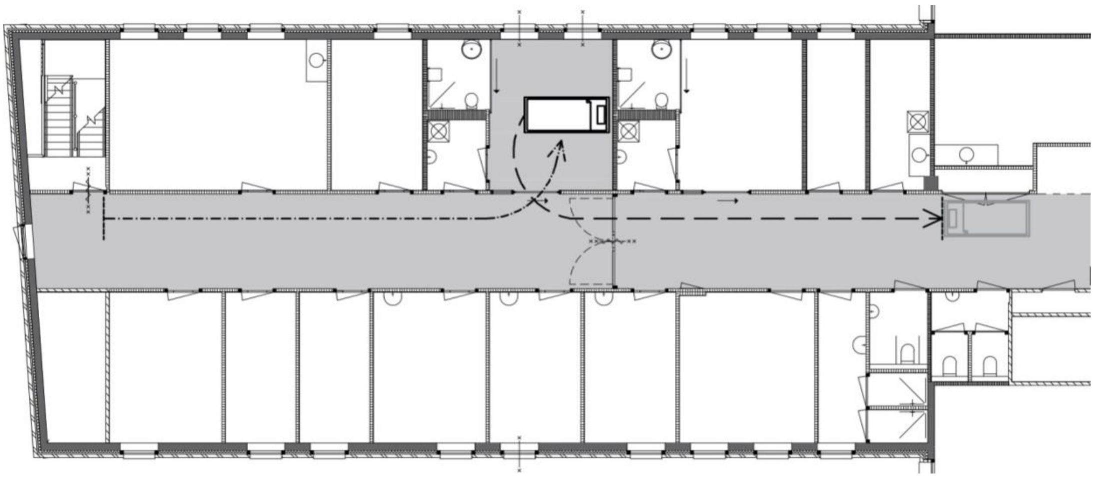


Figure 5.1 Evacuation route of dialysis patient (1:200).

	Arrival speed 1st round [m/s]	Arrival speed 2nd round [m/s]	Uncoupling time 1st round [s]	Uncoupling time 2nd round [s]	Leaving room 1st round [s]	Leaving room 2nd round [s]	Passing fire door 1st time [s]	Passing fire door 2nd time [s]	Evacuation speed 1st round [m/s]	Evacuation speed 2nd round [m/s]	Total time 1st round [s]	Total time 2nd round [s]	Experience
1	1,40	1,46	27	13	9	9	8	8	0,76	0,85	54,00	39	+
2	1,40	1,46	13	15	11	8	11	8	0,76	0,49	42,00	46	-
3	1,09	1,40	16	13	11	13	6	14	0,62	0,62	48,00	46	+
4	1,47	1,39	16	13	7	5	8	10	0,68	0,76	43,00	37	-
5	1,10	1,34	17	10	10	10	11	9	0,68	0,68	49,00	39	-
Avg.	1,29	1,41	17,8	12,8	9,6	9,0	8,8	9,8	0,70	0,68	47,2	41,4	

Table 5.5 Egress times of dialysis patient assisted by specialised staff.

When there is no specialised staff available, and a patient directly needs to be evacuated staff can decide to evacuate the patient with the dialysis machine. But then the uncoupling time and evacuating with the dialysis machine leads to a longer evacuation time. Evacuating without specialised staff is not preferable, and will take much longer time.

	Arrival speed [m/s]	Uncoupling time [s]	Leaving room [s]	Passing fire door [s]	Evacuation speed [m/s]	Total time [s]	Experience
1	1,40	41	21	17	0,53	84,00	-
2	1,40	65	24	27	0,23	128,00	-
Avg.	1,40	53,0	22,5	22,0	0,38	106,0	

Table 5.6 Egress times of dialysis patient when not assisted by specialised staff.

Intensive Care

On the Intensive care a patient is connected with one intravenous drip to six different pain and syringe pumps, which all had to be disconnected from the standard and placed on the bed of the patient. The patient was also connected with tube feeding, a catheter and extra oxygen supply. A monitor was used to measure blood pressure, heart monitoring and saturation. This can be switched to a small portable monitor when the patient must be evacuated.

During evacuation, specialised staff needs to choose which equipment can be disconnected and if the patient can be evacuated. Therefore, specialised staff is always necessary during evacuation of a patient of this type of ward.

During experiment the first couple was specialised staff, and did the two evacuation rounds by themselves. The following four couples didn't have experience with an Intensive Care, and did help one specialised staff member with disconnecting the equipment. Approaching the room and moving the bed was done by the couple who performed the experiment.

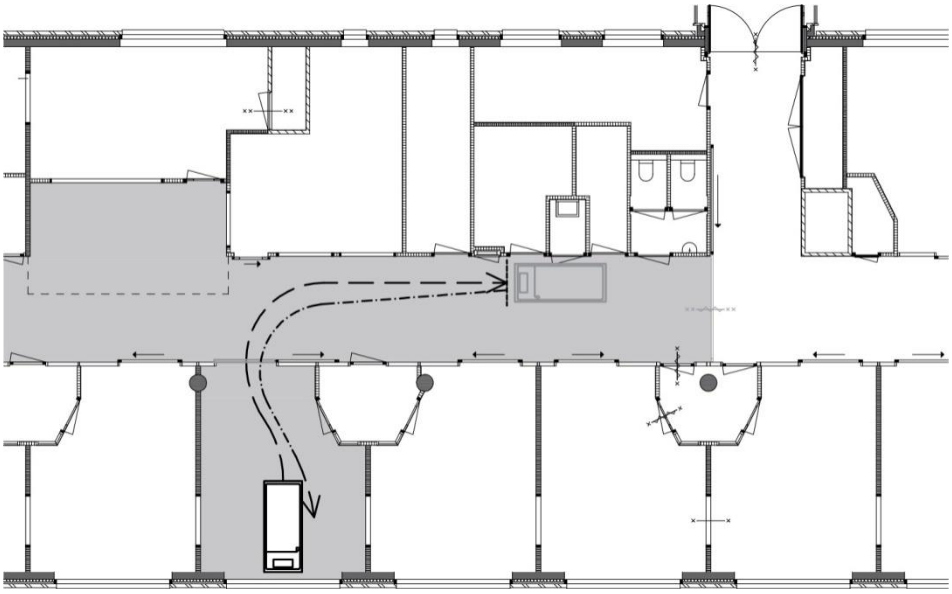


Figure 5.2 Evacuation route of IC patient (1:200).

	Arrival speed 1st round [m/s]	Arrival speed 2nd round [m/s]	Uncoupling time 1st round [s]	Uncoupling time 2nd round [s]	Leaving room 1st round [s]	Leaving room 2nd round [s]	Evacuation speed 1st round [m/s]	Evacuation speed 2nd round [m/s]	Total time 1st round [s]	Total time 2nd round [s]	Experience
1	1,30	1,17	120	73	8	9	1,16	1,16	144,00	99	++
2	1,46	1,67	118	51	7	8	1,16	1,35	140,0	72	-
3	1,17	1,30	117	84	11	8	0,68	1,16	150,0	108	-
4	1,46	1,67	100	67	8	5	1,35	1,35	122,0	85	-
5	1,95	1,95	94	68	8	6	1,62	1,35	113,0	86	-
Avg.	1,47	1,55	109,8	68,6	8,4	7,2	1,19	1,27	133,8	90,0	

Table 5.7 Egress times of Intensive Care patient assisted by specialised staff.

Neonatal ICU

The hospital were the experiments have been performed, didn't have a ward for only incubators. The hospital patient rooms are equipped for a mother with her new-born child. For the experiments there was an incubator and a patient bed without equipment placed. During the experiment, firstly the incubator has been evacuated, after this the basic patient was evacuated.

For evacuation the incubator needs to be switched off. After this the incubator had to be disconnected of oxygen supply, electricity, two syringe pumps and a monitor. During the first two drills more experienced staff preceded the disconnection and evacuation, but they didn't get help of the specialised staff member. The second couple was specialised staff who was used to work with the equipment. The last three couples didn't have experience with the equipment, and they did get instructions of the specialised staff, but preceded the evacuation by themselves.

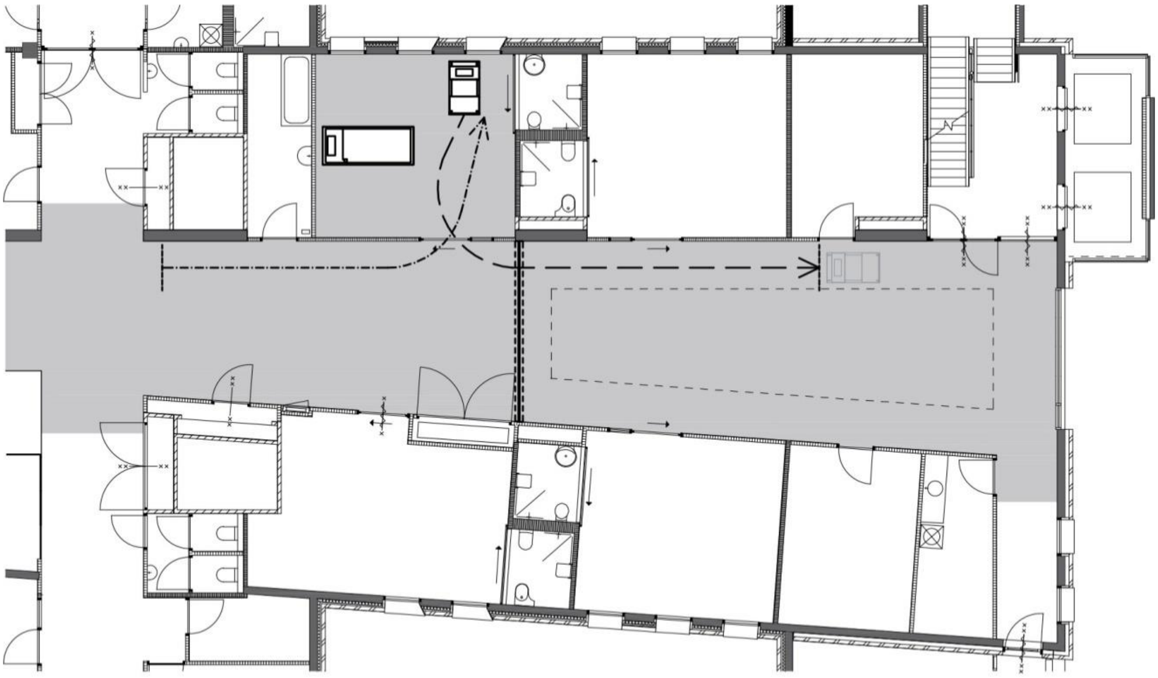


Figure 5.3 Evacuation route of incubator (1:200).

	Arrival speed 1st round [m/s]	Arrival speed 2nd round [m/s]	Uncoupling time 1st round [s]	Uncoupling time 2nd round [s]	Leaving room 1st round [s]	Leaving room 2nd round [s]	Passing stripe coil 1st time [s]	Passing stripe coil 2nd time [s]	Evacuation speed 1st round [m/s]	Evacuation speed 2nd round [m/s]	Total time 1st round [s]	Total time 2nd round [s]	Experience
1	1,40	1,40	91	40	17	6	-	-	0,81	0,93	131	66	+
2	1,24	1,60	35	25	6	6	5	4	0,93	1,08	61	48	++
3	1,24	1,40	72	27	6	12	4	7	0,93	1,08	98	57	-
4	1,40	1,60	74	31	4	4	6	7	1,08	1,30	96	51	-
5	1,60	1,87	42	23	5	4	6	0	1,30	2,17	64	40	-
Avg.	1,38	1,57	62,8	29,2	7,6	6,4	5,1	4,4	1,01	1,31	90,0	52,4	

Table 5.8 Egress times of incubator.

After evacuation the incubator needs to be as fast as possible connected to electricity and oxygen supply. Therefore coupling times of the incubator are also measured. Connecting was performed by one specialised staff member.

	Entering room [s]	Coupling time [s]	Total time [s]	Experience
1	5	53	58	++
2	5	57	62	
Avg.	5,0	55,0	60,0	

Table 5.9 Coupling times of incubator.

Basic patient

The evacuation time of a basic patient is measured. The patient in the bed was not connected to any equipment. For evacuation only the brakes of the bed had to be released, and the power plug of the bed needed to be disconnected. After this the bed could be moved.

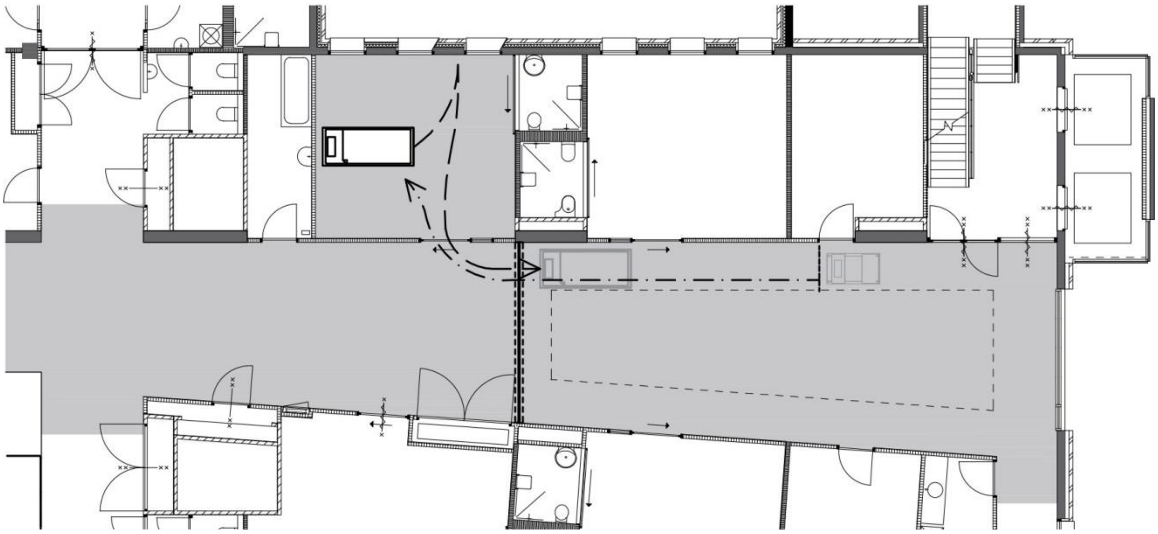


Figure 5.4 Evacuation route of basic patient (1:200).

	Arrival speed 1st round [m/s]	Arrival speed 2nd round [m/s]	Uncoupling time 1st round [s]	Uncoupling time 2nd round [s]	Leaving room 1st round [s]	Leaving room 2nd round [s]	Passing stripe coil 1st time [s]	Passing stripe coil 2nd time [s]	Total time 1st round [s]	Total time 2nd round [s]	Experience
1	1,37	1,54	6	5	13	10	-	-	-	-	+
2	1,54	1,54	4	4	10	7	10	8	32	27	++
3	1,54	1,54	8	5	4	10	10	6	30	29	-
4	1,37	1,54	9	4	10	7	5	5	33	24	-
5	1,54	2,05	6	4	18	8	4	4	36	22	-
Avg.	1,47	1,64	6,6	4,4	11,0	8,4	7,3	5,8	32,8	25,5	

Table 5.10 Egress times of basic patient.

Standard hospital ward

Data is gathered for a standard patient, which could be present on all regular hospital wards. The patient was connected to oxygen supply, with a connection on the wall. The patient was also connected to an intravenous drip, a catheter and two syringe pumps. The pumps were connected to the bed with a standard, and could be taken during evacuation. The connections to the wall of the pumps had to be disconnected.

The more experienced staff that performed the evacuation rounds, as well the less experienced staff performed the evacuation round by themselves, and didn't get instructions during an evacuation round.

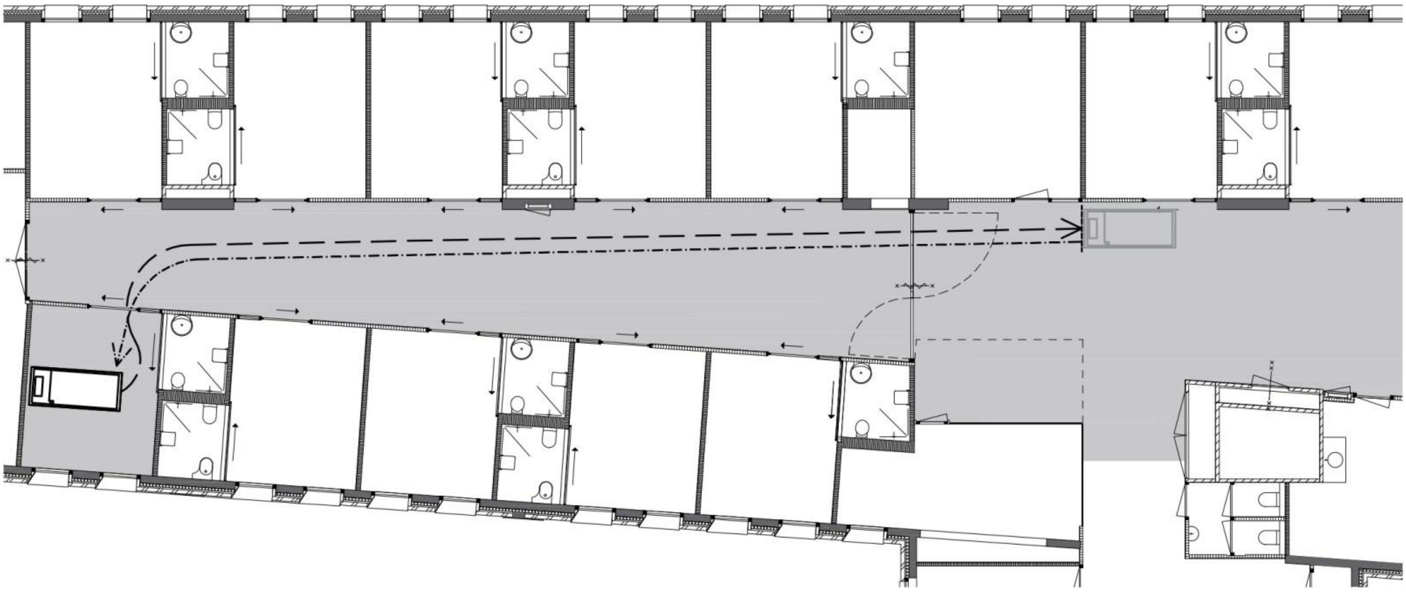


Figure 5.5 Evacuation route of regular patient (1:200).

	Arrival speed 1st round [m/s]	Arrival speed 2nd round [m/s]	Uncoupling time 1st round [s]	Uncoupling time 2nd round [s]	Leaving room 1st round [s]	Leaving room 2nd round [s]	Passing fire door 1st time [s]	Passing fire door 2nd time [s]	Evacuation speed 1st round [m/s]	Evacuation speed 2nd round [m/s]	Total time 2nd round [s]	Total time 1st round [s]	Experience
1	1,61	1,52	30	23	7	13	6	7	2,03	2,61	63,00	60	++
2	1,62	1,52	41	35	13	12	6	7	1,66	1,22	83,00	79	-
3	1,40	1,30	27	31	14	12	5	5	2,03	1,53	69,00	74	++
4	1,58	1,56	24	23	14	13	7	9	3,05	3,66	63,00	59	-
5	1,56	1,66	45	28	14	13	7	7	1,02	1,53	94,00	70	+
Avg.	1,55	1,51	33,4	28,0	12,4	12,6	6,2	7,0	1,96	2,11	74,4	68,4	

Table 5.11 Egress times of regular patient.

Recovery

On the recovery ward only a small distance could be used for the evacuation round. The doors in the evacuation route were electric and couldn't be deactivated. Therefore the results of passing the door are not implied in the overall results.

The patient was connected to equipment what is regular for a Recovery ward. On this ward patient just had surgery, and stay temporary on this ward. Therefore the equipment is mobile, more than other wards. The patient was connected to oxygen supply, an intravenous drip and a bear hugger for heating. The patient was also connected to a monitor, which was used for saturation, blood pressure and heart monitoring. During an evacuation the monitor can be disconnected and switched to a small portable monitor.

During the evacuation rounds not experienced staff get instructions, but performed the uncoupling and disconnecting by themselves.

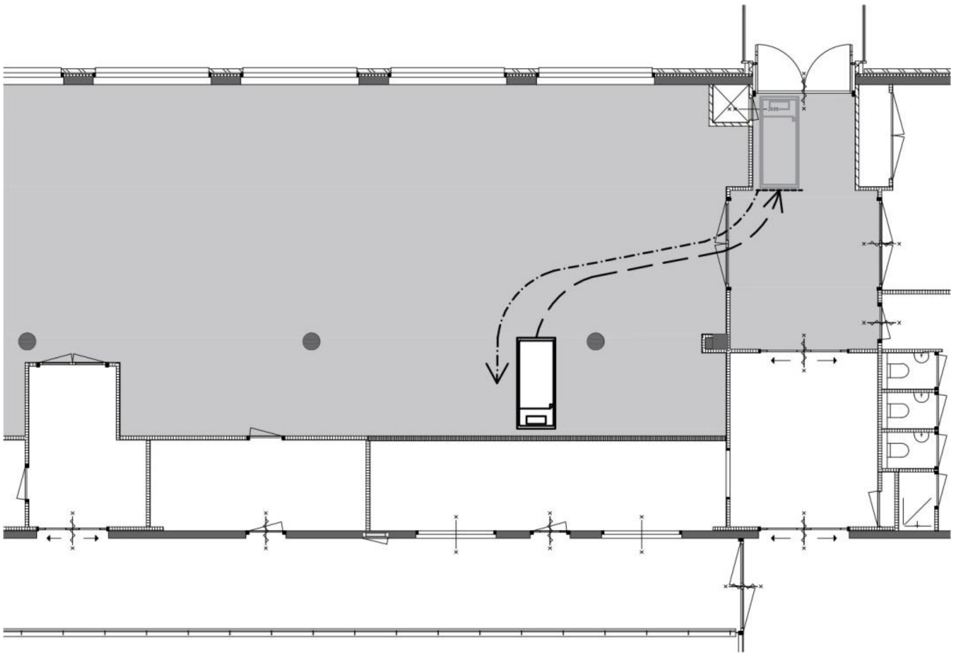


Figure 5.6 Evacuation route of recovery patient (1:200).

	Arrival speed 1st round [m/s]	Arrival speed 2nd round [m/s]	Uncoupling time 1st round [s]	Uncoupling time 2nd round [s]	Evacuation speed 1st round [m/s]	Evacuation speed 2nd round [m/s]	Total time 1st round [s]	Total time 2nd round [s]	Experience
1	1,62	1,39	47	20	0,58	0,58	67	41	-
2	1,39	1,21	28	15	0,51	0,54	51	38	+
3	1,39	1,39	29	31	0,54	0,74	51	49	-
4	1,39	1,62	58	24	0,48	0,58	82	44	-
5	1,39	1,62	17	16	0,48	0,74	41	33	++
Avg.	1,43	1,44	35,8	21,2	0,52	0,63	58,4	41,0	

Table 5.12 Egress times of recovery patient.

Heart monitoring

On the heart monitoring ward staff could precede a full evacuation round. The patient was connected to more extensive heart monitoring equipment, namely an ECG. The patient was also connected with saturation, to measure the amount of oxygen in the blood. The patient was also connected with a blood pressure meter.

During the evacuation rounds all couples disconnected the patient by themselves, and some less experienced staff did get small instructions by a specialised staff member on how to disconnect the equipment.

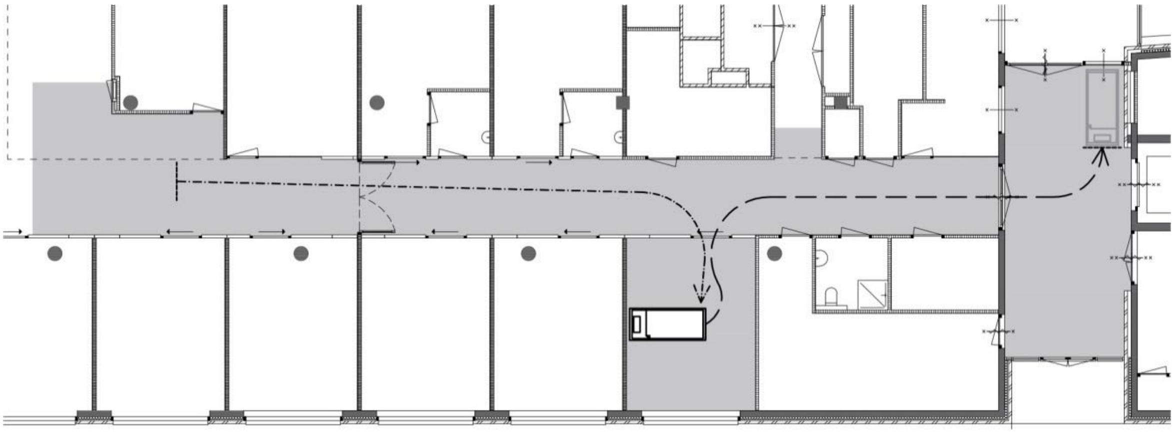


Figure 5.7 Evacuation route of heart monitoring patient (1:200).

	Arrival speed 1st round [m/s]	Arrival speed 2nd round [m/s]	Uncoupling time 1st round [s]	Uncoupling time 2nd round [s]	Leaving room 1st round [s]	Leaving room 2nd round [s]	Passing fire door 1st time [s]	Passing fire door 2nd time [s]	Evacuation speed 1st round [m/s]	Evacuation speed 2nd round [m/s]	Total time 1st round [s]	Total time 2nd round [s]	Experience
1	0,98	1,17	51	19	8	8	8	7	1,33	0,95	76	44	++
2	1,30	1,46	69	24	8	6	8	6	1,33	1,33	91	43	-
3	1,06	1,06	24	25	7	20	5	4	1,11	0,83	48	64	-
4	0,90	0,98	49	27	11	11	7	6	0,60	1,11	84	56	-
5	0,98	1,06	27	20	8	7	6	5	0,83	1,11	55	44	-
Avg.	1,04	1,15	44,0	23,0	8,4	10,4	6,8	5,6	1,04	1,06	70,8	50,2	

Table 5.13 Egress times of heart monitoring patient.

Overview of experiments

The uncoupling times are displayed on the table below. There are big differences between the wards on how long it takes to uncouple the patients.

The experiments also showed that there is a difference in the time required for uncoupling during the first and the second round. During the first round all staff was searching for what to disconnect, and in which order. When they right after the first round performed their second round, also inexperienced staff achieved much faster uncoupling and disconnecting times. So if staff is regularly trained with disconnecting patients on different types of wards, much faster egress times of hospital wards can be achieved.

	Dialysis [s]	Intensive Care [s]	Neonatal ICU [s]	Basic patient [s]	Regular patient [s]	Heart monitoring [s]	Recovery [s]
Average of first round	17,8	109,8	62,8	6,6	33,4	44,0	35,8
Average of second round	12,8	68,6	29,2	4,4	28,0	23,0	21,2
Total average	15,3	89,2	46,0	5,5	30,7	33,5	28,5

Table 5.14 Uncoupling times of specific wards.

The general parts of the evacuation, such as approaching the room, evacuating with the bed, and passing a fire door or a stripe coil with a bed are combined in the table below. Also the time for leaving a patient room with a bed is determined. All used patient rooms were single patient rooms and there can be differences with other patient rooms for multiple patients, where there is maybe more space to manoeuvre.

	Arrival speed [m/s]	Leaving room [s]	Evacuation speed [m/s]	Passing fire door [s]	Passing stripe coil [s]
Average	1,42	9,3	1,23	7,4	5,5

Table 5.15 Egress times of specific parts of evacuation.

With this gathered data egress calculations can be made for evacuation times of different type of wards, and the specific parts during an evacuation can be implied in these calculations.

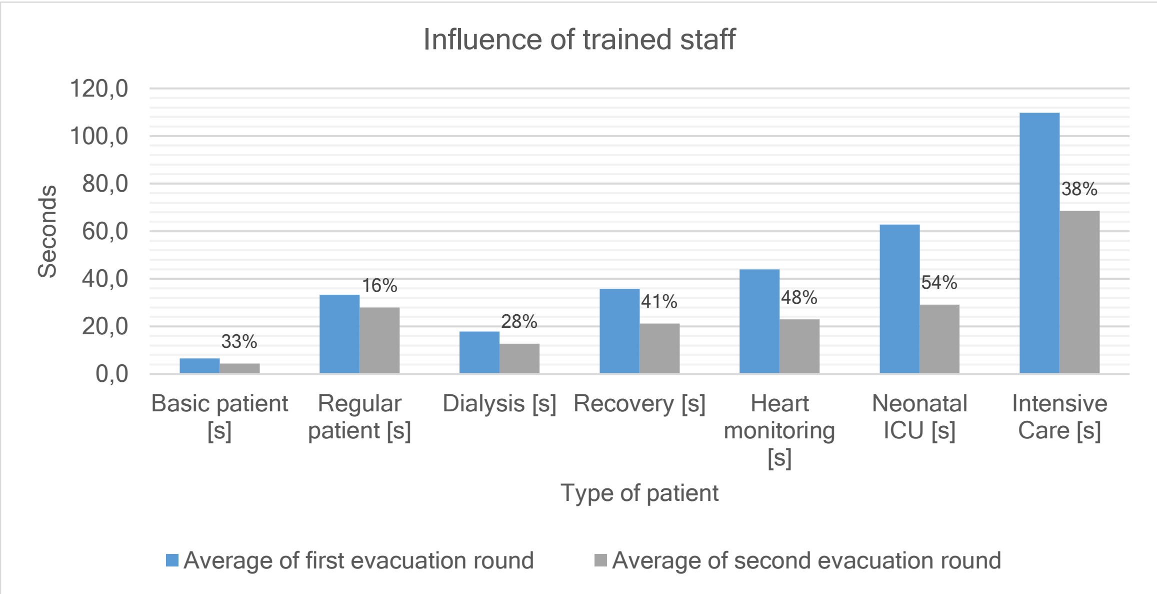
Important observations

The evacuation drills also showed that it is difficult for staff to always close the doors to the patient rooms, to prevent smoke from entering the patient room. The doors on the ward where not self-closing. Almost all doors of patient rooms where open when the drill started. Because there was a simulated fire with smoke production in the corridor, doors of patient rooms should be closed as quick as possible. The staff present during the evacuation first closed the doors, and then started the evacuation.

The doors should be kept close as much as possible, but when staff entered the room to prepare the patients for evacuation the doors remained open. Patients and staff in the room preparing for evacuation are already affected by smoke, where this could be avoided if the doors are closed. Patients, but especially staff are longer affected by smoke then it is accepted. When the first patients are evacuated out of the room, the door remained open. Patients still in the patient room are already affected by the smoke. Closing the doors should be done more carefully, so that patients will be affected as less as possible by smoke.

If staff isn't used to the evacuation procedures, it´s likely that delay occurs during evacuation. Experiments showed that if staff doesn't know exactly what to do, there is time lost in coordination between the different staff members. With more training this delay can be prevented.

The influence of the level of trained staff could be evaluated out of the experiments performed on the specific wards. On every ward evacuation rounds of evacuating the same patient are performed two times per couple. The experience of working with the equipment of the evacuation couples differed. But the results as seen in graph 5.16 show that the uncoupling time per patient decreased accordingly. Considering that all staff, as well experienced staff and staff who are not used to work with the equipment, must be able to contribute to a fast evacuation regular training on disconnecting different types of patient is necessary for all staff members. This can contribute to a faster evacuation of all types of wards.



Graph 5.16 Difference in first and second evacuation round performed during experiments.

6. DESIGN GUIDELINES

Design tool

The aim to have design guidelines for an integrated fire safety concept can be achieved by creating a design tool, in which all different parameters can be added. The design tool can calculate a relative risk for a fire occurring, and with the probability of a fire occurring the relative of casualties on the ward. Additionally, the Required Safe Egress Time of a ward can be determined and calculated. With the design tool calculating a relative risk and total RSET for a new design compared to the ward, fulfilling the demands of the regulations, a more flexible interpretation is possible. A more integrated fire safety concept can be already a part of the design process at an early stage.

Important for the approach, is the Required Safe Egress Time of a specific hospital ward. If the RSET is longer than the Available Safe Egress Time (ASET), casualties will appear also in rooms other than the room of origin. If it is possible to evacuate the room of origin is always influenced by a lot of factors of the fire spread, and difficult to predict.

The lay-out of a ward, with fire compartments and staff present must be in such a way that other patients from different rooms can be evacuated. Changes in the fire safety concept can make sure the probability of a fire occurring or fire growth is lower, so the ASET will be longer. The RSET can be shorter so the relative probability of casualties can be lower. This comparison can be made by using the probability approach compared with the validated data about egress times for specific hospital wards.

The goal of the design tool is to help designers and board of directors of hospitals with insights in effectiveness of different measures and the investment costs to see what the impact is on the safety level. With the design tool a balance can be made between a desired safety level and the different options to be able to increase the safety level, and the related cost of the different options. The design tool gives also insight in how much staff is needed to achieve a certain level of safety.

Probability calculation

As bases for the design, a probability calculation is created per specific hospital ward, with different probabilities implemented. For the starting point of the relative probability calculation, it is important to consider the probability of a fire that will occur in hospitals. The occurrence of a fire in hospitals is 0,0007 * α per m2 per year (Ramachandran et al., 2004). The value of the probability for an increase in building size is α, for hospitals this is 0,75. This value is based on data of insurances, the probability of a starting fire. In the probability of a fire developing it is necessary to consider fires that do not go out with those that pose a serious threat.

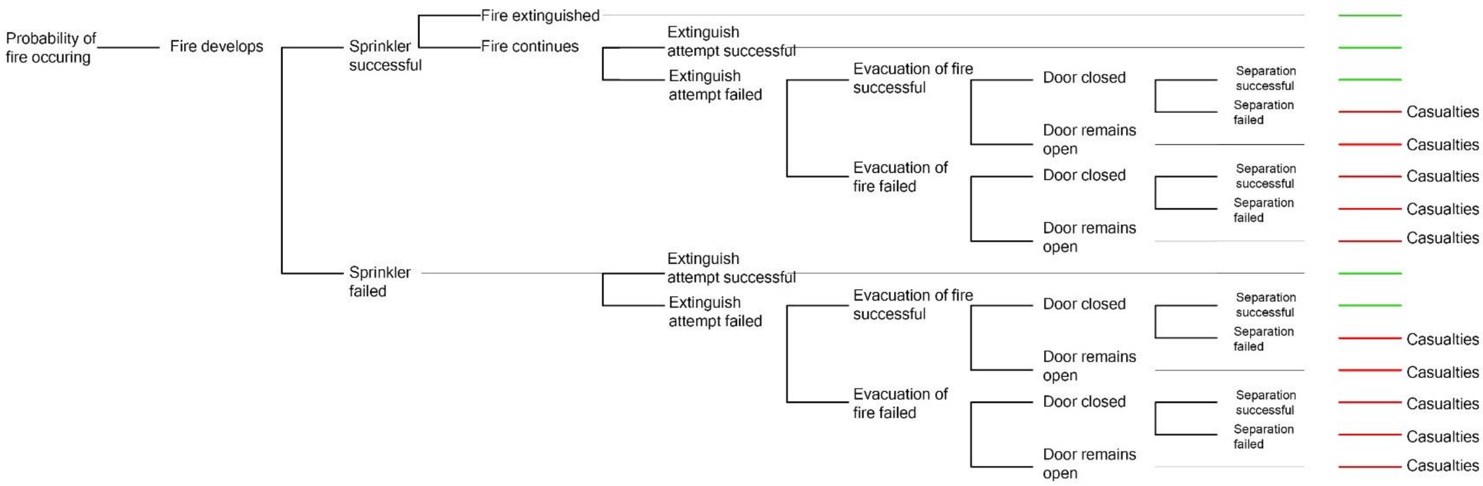


Figure 6.1 Probability approach.

With the design tool an actual risk for the ward can be calculated. The following probabilities should be determined and must be added in the design tool;

- Fire development with strict material restrictions in corridor;
- Fire development with strict material restrictions in patient rooms;
- Extinguish attempt successful;
- Evacuation room of origin successful;
- Probability doors will be closed by staff if room of origin is evacuated successful;
- Probability doors will be closed by staff if room of origin is not evacuated successful;
- Effectiveness of self-closing doors;
- Sprinkler successful;
- Potential smoke development when sprinkler is successful;
- Failure of separation.

About the different phases of important event during a fire in hospitals is no data available. It was impossible to determine exact probabilities based on actual available data. Therefore, some probabilities are assumed with a certain percentage, which seems to be likely. With more data an actual risk of casualties could be calculated for a ward, instead of the relative probability.

For example, the change of a successful extinguish attempt is estimated as a 50% chance. Because this chance is the same in all calculations, it has no effect on the difference between the proposed design and the designs based on the building regulations. However, one should not look at the exact value of the probability but should only look at the relative probability (in other words, one can only compare results of one fire safety concept with another)

The design tool includes options for material restrictions in the corridor and patient rooms. If in the design choices are made to decrease the chance of a starting fire and development of a fire, the probability is lower. To be able to influence the calculation the there is a 50% probability added. The exact material restrictions to make sure this value is reached should be further determined.

Probability of staff closing door and self-closing doors

There is no data available about the chance staff will close doors during an emergency, or a self-closing door will be closed. The experiments showed that staff tend to forget to close the door hence the procedure is to close them. But because there was no actual threat of smoke spreading, no reliable value can be determined. Therefore, the probability of staff closing door is 50%. But experiments showed that if there are still patients in a room, staff tend to leave the door open. To ensure this has an effect in the probability calculation, the probability of staff closing door while there are still patients in the room, is assumed as a 25% chance.

A design option is to use self-closing doors of the patient room in a design of a ward. In designs of wards based on the Dutch Building Decree with separations to be sure patient rooms are sub fire compartments, self-closing doors are mandatory. There is no data available of the effectiveness of self-closing doors during emergencies. It is assumed that the self-closing doors are reliable, and therefore a 90% probability is used that self-closing doors will close during an emergency.

Evacuating room of origin

There is no knowledge available about the chance staff can evacuate patients out of the room of origin, and it will depend strongly on the size if the fire ignited, and the materials used. This probability is therefore kept as a 50% chance. More research and more details about the materials used will be necessary to be able to make better predictions.

Effectiveness of sprinkler system

A solution for increasing the fire safety of hospitals can be by using a sprinkler system. A sprinkler system will be able to increase the available safe egress time. When a sprinkler system is activated by a starting fire, it can keep the fire from growing so there is no direct threat to adjacent fire compartments. When a sprinkler system is activated it is likely to say that the fire will not spread through an entire building. But the fire can be controlled by a sprinkler, but a sprinkler is no guarantee that a fire will be extinguished. But because there is already a starting fire, and the sprinkler is designed to control the fire and will therefore not always extinguish the fire, there is still smoke production. This smoke production can be toxic so the fire compartment will always need to be evacuated as fast as possible, but a longer ASET is possible.

Sprinkler systems can be used for realisation of larger fire compartments, or to omit sub fire compartment separations. A sprinkler system will reduce the fire and smoke development, and therefore create a longer available egress time. Hence an evacuation of the fire compartment will still be required. If a sprinkler is used in combination with an SHEVS the available egress time of the compartment will be further prolonged. (TNO, 2012). The installation of a sprinkler system seems to be only technical practicable when a hospital is new build or undergo a big renovation. Applying a sprinkler system in an already existing building is often considered too expensive.

If a sprinkler system will serve as a solution in the probability calculations, a probability of failure of the sprinkler system needs to be considered. After research, it is stated that the highest probability of a sprinkler system effectiveness seems to be between 90% and 95% (Frank et al. 2013). A lot of factors will still influence the effectiveness of a sprinkler system. For example maintenance, will need to be secure, to maintain a high probability of a working sprinkler system. In the probability approach a factor of smoke spread is still implanted. Closing doors by staff or self-closing doors still have an effect on the relative risk on casualties.

The probability a fire that will develop when sprinklered or not sprinklered depends on the area initially ignited. The conceptually approach does not allow to give a prediction about the size of this area. However, there is data available over fires which were controlled by sprinklers. Data gathered over European statics over a 10 year-period give that in buildings fully protected by sprinklers 60% of fires were controlled by the spray from no more than 4 sprinklers.

In the probability calculation, which is part of the design tool, a sprinkler is considered as measure to reduce the risk. Despite to give a prediction about the probability a fire will be controlled with sprinklers, the area ignited is necessary, but the value of 60% is used in the approach. This value represents the direct need for evacuation. When a fire is controlled with sprinklers, evacuation will be still necessary but the risk for fire development has passed.

Probability of failure of separation

If doors are closed, there remains still a probability of failure of the separation. In the design tool, it is assumed that all separations on a ward are 30 minutes fire protecting. The Dutch standard NEN 6079 is used for approaching fire design of industrial buildings based on probabilities. In this standard, a probability for failure of separations is included. The chance of failure of a standard separation wall of 30 minutes with passages is 11% (NEN 6079, 2016).

Overview of different probabilities

The probabilities as displayed in table 6.1, are used in the calculation approach of the design tool. Due the lack of data the actual risk of casualties can´t be calculated for a design. Therefore, a relative calculation approach is used, where some probabilities are assumed to be able to have an effect on the relative chance, compared with a design based on the maximum restrictions of the current regulations.

Probability	[%]
Fire development with strict material restrictions in corridor	50%
Fire development with strict material restrictions in patient rooms	50%
Extinguish attempt successful	50%
Evacuation of room of origin successful	50%
If evacuation of room is successful, probability door will be closed by staff	50%
If evacuation of room is unsuccessful, probability door will be closed by staff	25%
Probability self-closing doors will effective be closed	90%
Successful sprinkler	90%
Potential smoke development after working sprinkler installation	40%
Failure of separation during fire	11%

Table 6.1 Overview of assumed probabilities.

Design

To be able to compare a proposed layout of a new design, to the current regulations, four different types of layouts are taken as limited values. The layouts are based on the maximum restrictions as they are stated in the regulations. There are differences between the restricts for new buildings, and already existing buildings. The compartments for existing buildings can be twice as large as new buildings. Therefore, the number of patients in layouts full filling the restrictions about existing buildings is twice as high.

There also need to be a difference made between wards with permanent surveillance and without. In wards without permanent surveillance the patient rooms must be designed as sub fire compartments with self-closing doors. If there is permanent surveillance no separations are required. In the design tool, it's possible to choose to which regulations the design proposal needs to be compared.

	Surveillance	Surface compartment	Patients
DBD 2012	Permanent surveillance	500 m2	30
DBD 2012	Without permanent surveillance	500 m2 (50 m2 sub fire compartment)	36 (6 x 6p.)
DBD existing buildings	Permanent surveillance	1000 m2	60
DBD existing buildings	Without permanent surveillance	1000 m2 (100 m2 sub fire compartment)	72 (6 x 12p.)

Table 6.2 Size of fire compartments, where design is compared with.

Required Safe Egress Time

With the design tool a RSET can be automatically calculated with the design tool. To be able to determine the time it takes for staff to evacuate a bed to the next fire compartment and arrive back to the next patient to be able to evacuate the following patient. The following times must be determined and should be added in the design tool;

- Pre-movement time of staff,
- Extinguish attempt,
- Uncoupling time for a specific patient on ward,
- Time to leave patient room with bed.

The following distances and walking speeds need to be added;

- Average evacuation distance per patient
- Evacuation speed,
- Average arrival distance per patient,
- Arrival speed,
- Time to pass a fire door with bed

An evacuation needs to be performed by the staff members present on the ward. For the calculations it is assumed that two staff members will evacuate one patient at once. Strategies in hospitals is that when an emergency occurs, extra staff members can be called to help performing an evacuation of a ward. Therefore, the following parameters need to be added to the design tool to calculate the total evacuation time of the ward;

- Staff present,
- Number of extra staff members who will arrive,
- Arrival time of extra staff members.

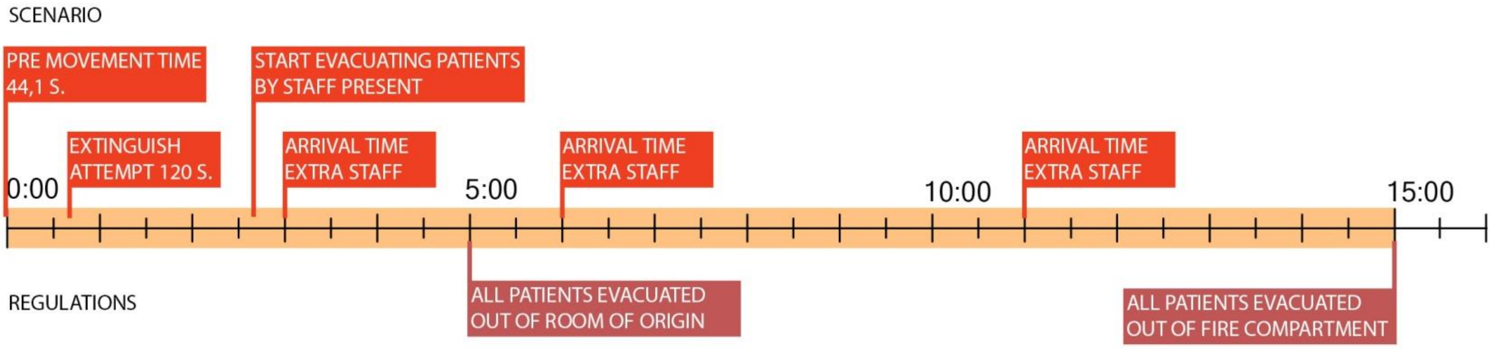


Figure 6.2 Timeline as basis for RSET calculation

The equations to calculate the total RSET of a ward in the design tool are;

$$Average\ RSET\ of\ ward = \frac{Response\ time\ [s] + Extinguish\ attempt[s] + (Evacuation\ time\ per\ patient\ [s] \times Amount\ of\ patients)}{Staff\ present + (extra\ staff - arrival\ time\ [s]) + \ (extra\ staff - arrival\ time\ [s]) + \ \dots}$$

Equation 6.1 Average RSET of hospital ward.

$$Evacuation\ time\ per\ patient = \frac{Arrival\ distance\ [m1]}{Arrival\ speed\ [^{m}/_{s}]} + \ Uncoupling\ time\ [s] + Leaving\ room\ [s] + \ Passingfire\ door\ [s] + \frac{Evacuation\ distance\ [m1]}{Evacuation\ speed\ [^{m}/_{s}]}$$

Equation 6.2 Evacuation time per patient.

To be able to determine a more reliable value for the RSET of a ward, a deviation for the total time is calculated. With this value, it is possible to state what the average time for evacuation of the total ward is, but also the time in which 84% of the evacuations must be able to proceed successfully.

$$(\sigma)^2 = \left(\frac{\partial d\ [m1] \times a}{s\ [^{m}/_{s}]} \right)^2 \times \sigma^2 + \ (a \times \sigma)^2 \ + \cdots$$

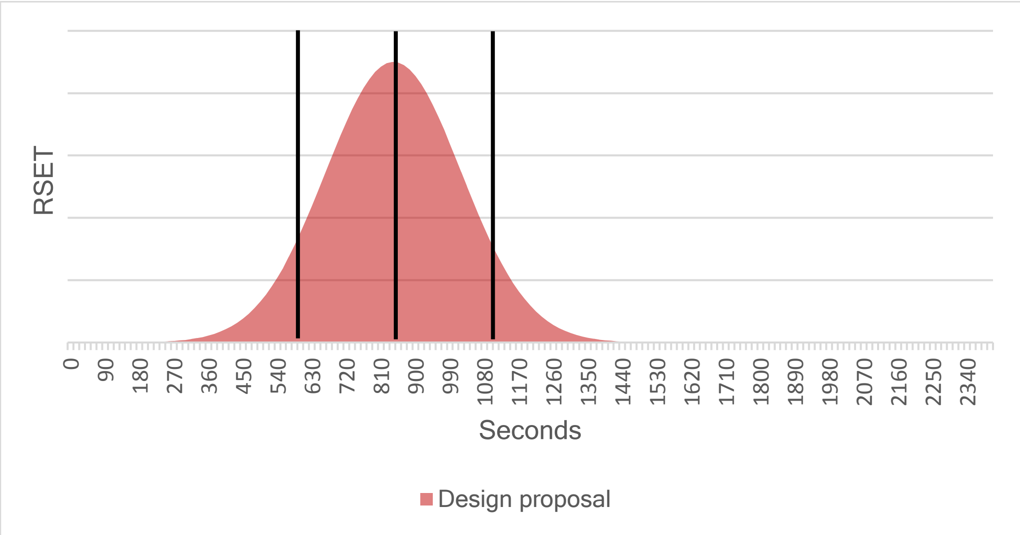
Equation 6.3 Total deviation ward (Berendsen, 2006).

$$Density = \frac{e^{-\frac{1}{2}}(x-\mu)' \sum^{-1}(x-\mu)}{\sqrt{(2\pi)}^{n}}$$

Equation 6.4 Multivariate normal distribution.

A calculated RSET is displayed in graph 6.1. The top of the distribution represents the average value for the calculated RSET. It is likely that most of the evacuations performed will be able to will be close to the average. The boundary’s set by the normal deviation are placed on a deviation of 34% deviating from the average value. It is stated that in the average RSET plus 1 standard deviation, 84% of the evacuations must be able to be carried out in the calculated total time.

Defining the RSET with standard deviation, will give greater guarantee that the evacuation will be completely carried out within the given time



Graph 6.1 RSET-with standard deviation of 34%.

The data gathered from the experiments performed on the different wards can be used to determine the standard deviation of every part of the evacuation path. Deviations are included in the following table;

	Arrival speed [m/s]	Uncoupling time Dialysis [s]	Uncoupling time Intensive care [s]	Uncoupling time incubator [s]	Uncoupling time basic patient [s]	Uncoupling time standard patient [s]	Uncoupling time Recovery [s]	Uncoupling time Heart monitoring [s]	Leaving room [s]	Passing fire door [s]	Passing stripe coil [s]	Evacuation speed [m/s]
Measurements	100	10	10	10	10	10	10	10	60	30	18	60
Standard deviation	0,27	4,60	24,45	24,07	1,78	7,56	14,07	16,79	3,51	2,13	2,03	0,62
Average	1,46	15,30	89,20	46,00	5,50	30,70	28,50	33,50	9,28	7,37	5,39	1,12
1 std. Dev. Min.	1,19	10,70	64,75	21,93	3,72	23,14	14,43	16,71	5,78	5,24	3,36	0,51
1 std. Dev. Max.	1,73	19,90	113,65	70,07	7,28	38,26	42,57	50,29	12,79	9,49	7,42	1,74
%	78,0%	80,0%	60,0%	70,0%	80,0%	60,0%	80,0%	80,0%	68,3%	70,0%	83,3%	83,3%

Table 6.3 Standard deviations of specific parts of evacuation.

Staff:patient ratio

A certain number of staff is always present on a hospital ward. It is stated that during night-time the smallest number of staff is present per patient. This so called staff:patient ratio for a fire safety concept normative. A hospital always decides for itself what kind of staff:patient ratio they require per ward. A staff:patient ratio of 2 staff members per 24 to 32 patients seems to be occurring frequently, depending on the specific ward. In for example Intensive Care Units the staff:patient ratio is much higher. This can be 1 staff member per 3 or 4 patients.

Important for the probability calculation is also the response and arrival time of extra staff members who can assist during the evacuation of the ward. Also important is, whether the staff members that are already present on the ward are able to perform an extinguish attempt.
The staff:patient ratio and ratio of trained staff will always need to be determined exactly by the hospital, and the consequences of these ratios will be factors that need to be incorporated in the design.

Emergency response fire brigade

The arrival time of the fire brigade is stated to be a maximum of15 minutes after the activation of the fire alarm. Fire alarms in hospitals must be directly connected with the fire station. Staff of the hospital must try to evacuate all patients or other persons out of a fire compartment before the fire brigade arrives. Therefore, in calculations 15 minutes can be assumed as boundary condition. Hospitals must try to achieve a full evacuation of a ward (fire compartment) within 15 minutes.

Use of central audible fire alarm

Using a central audible fire alarm in emergency situations could be a solution for a faster evacuation. This could be an option for patients or other people such as visitors who are self-reliant, or have limited self-reliance but can evacuate without assistance. These people could start to evacuate without the help of staff. This could affect the total egress time per ward, because it is likely that staff should evacuate less patients and could concentrate on the more vulnerable patients.

The current strategy of most hospitals is a silent alarm. If there is a fire emergency, staff get an alert on their personal devices. They will check first if there is a direct need for evacuation, and then will start the evacuation if necessary, by warning patients and visitors, assisting them or disconnecting and evacuating them out of the fire compartment. The main reason for not using a central audible alarm, as stated by the hospitals, is to avoid distressing people in case of a false alarm. The likelihood of a false alarm is greater than that of a real alarm. An audible alarm will interrupt the regular processes of care in hospitals too much when there is no need to evacuate. It is possible to have a faster detection of the fire with a central alarm, but this will lead to an increase of the risk of false alarms.

Another reason why hospitals tend not to use a central audible alarm is that they want to keep control over the emergency situation. Staff will decide which ward to evacuate when, and in which direction. Patients and people evacuating on their own will cause panic and must be avoided in hospitals. Therefore, using a central audible alarm is not an option for faster evacuation of hospitals.

Comparison with Dutch Building Decree

The designs are compared with two different types of wards of the Dutch Building Decree. The first variant is a maximum surface of 500 m2, with patient rooms as sub fire compartments with of a maximum of 50 m2. These sub fire compartmens must have self-closing doors.The second variant of layouts can be fire compartments of 500 m2, without any seperations if there is permanent surveillance. For comparison wards are designed on the maxium allowable restrictions of the regulations.

In the current regulations there are no restrictions about egress times of not self reliant persons included, only about for example the flow capacity of doors. But guidelines drafted in 1994 give some information of principles hospitals should be able to full fill, with designs sufficent to the Dutch Building Decree. These guidelines state for wards with reliant people;

- Within 1 minute after ignition alarming to staff and fire-fighters.
- Within 4 minutes after alarming patients are evacuated out of room of origin.
- Within 15 minutes after alarming staff evacuated all patients out of fire compartment.
- Within 15 minutes after alarming fire-fighters operational to be able to initiate an extinguish attempt.

These times are important boundary conditions for the designs of the wards. Hence the guidelines don't give restrictions about the maximum evacuation time for patients in a scenario when a fire starts in a corridor or an auxiliary room. If a fire starts in these area's patients should be evacuated through the room of origin for a longer time then 4 minutes.

Results

The design tool gives two different outputs. The first output is the relative probability of casualties, based on a probability of fire occurring per square meter. With different probabilities in the approach, a relative risk can be calculated. By making a calculation for a ward based on the current regulations, a comparison can be made between a new design and current regulations.

The risk of casualties is calculated with a relative risk, because for most probabilities not enough data was available to be able to be established accurately. Therefore, the risk of casualties is calculated with the assumed probabilities, and compared with a design based on the maximum restrictions of the Dutch Building Decree. While approaching these layouts with the calculation approach with the same probabilities, the results can be compared. The risk on casualties for a design proposal is given as a relative percentage, where a layout based on the maximum restrictions of the DBD is stated as a 100% risk.

In the relative risk of casualties, a difference is made between the direct influenced patients, and the indirectly influenced patients. Direct influenced people are in the room of origin, and the design has low possibilities to decrease this value. But the indirectly influenced patients are in different rooms on the ward. By changing the design options, and decreasing the required egress time, the risk of these patients can be significantly decreased.

With the input of a new design, and extra parameters for certain parts of the evacuation a Required Safe Egress time can be calculated. By calculating both a RSET for the new design, as for a ward based on the current regulations the effect of the total RSET is displayed. Changing or adding several parameters on both the layout, or the organisation of staff of the hospital, can decrease the RSET of a ward, and therefore make the ward significantly safer.

Design guide

With the design tool a fast analysis can be made about the fire safety level of a design. During the design phase the relative risk and the RSET can be calculated, and be adapted to be a real tool which can be used to create different options and to create a most optimal design proposal.

The design tool must be filled in in different steps, namely;

- The first step is to fill in the number of patient rooms, their surface and the number of patients present in the room. Also, surfaces of the auxiliary rooms and the corridor need to be entered. After this some design options can be included to reduce the risk. This are options to choose a sprinkler installation, self-closing doors and material restrictions.

- The second phase of the calculation the RSET is determined. For this the type of ward needs to be selected, so the uncoupling time of the specific patients can be included. The average evacuation distances must be included, which need to be travelled to be able to calculate the walking times for staff. The number of staff members present, and the number of staff members with their arrival time who come to assist the evacuation procedure, need to be inputted to determine the actual RSET, considered the number of staff members.

- The last step is to choose the regulations where the design must be compared to. Options are the regulations for existing buildings, or the restrictions for new buildings. A different option is of a design can be compared with a ward with permanent surveillance of staff, or has separation to create sub fire compartments.

- The results give an actual risk on casualties for the design compared with a layout based on the maximum allowable restrictions of the chosen type of Building Decree. The RSET of the design calculated can also be compared with an RSET for a ward based on the building regulations. The number of staff members and their arrival time is equal for both calculations.

7. DESIGN CASES

Design cases

To show how the design tool works, and how it can be a usable while designing, three different types of cases are explained.

With the design tool for every lay out a risk of fire occurring can be determined. Beside the RSET with standard deviation can be calculated. The probability of a fire occurring and the RSET of a ward gives an indication on what the level of risk or safety is for the design of a hospital ward.

The different layouts that are explained and calculated are three total differing wards. The first calculated layout is a ward such as it is existing in older hospitals. The design case must give insight in the present situation, and how it can be improved to an acceptable level.

The second layout is a ward based on the changing design strategies, with less patient in a fire compartment. But patients are placed in single patient rooms, and a wider corridor with changing risks is designed.

The last design case is an option for an intensive care ward. With the data gathered and the insight in the actual disconnecting and evacuating times the design is adapted to a more acceptable level of risks and evacuation times.

In the appendix more designs are added, to see what the effect of different types of layout is on the results in the design tool.

Regular hospital ward

The first layout calculated is a typical ward for existing hospitals.

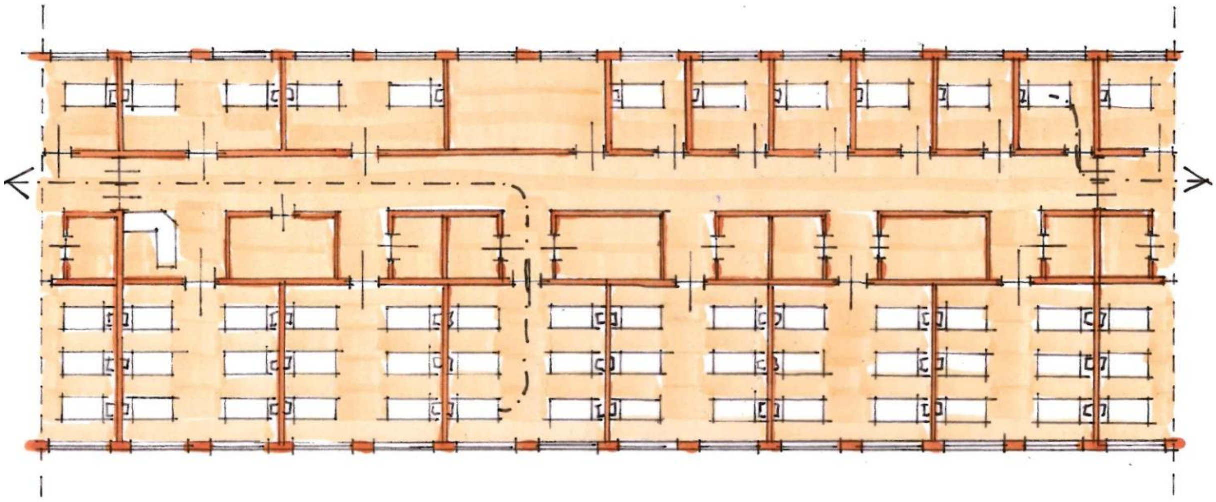


Figure 7.1 Proposed layout of regular patient ward.

The input values of the existing ward are;

Surfaces:	6 patient rooms of 6 persons of 50 m2 2 patient rooms of 2 persons of 27,7 m2 6 single patient rooms of 13,5 m2 Auxiliary rooms of 157,6 m2. Corridor of 156 m2
Evacuation:	Standard patients Average evacuation length of 30,8 m1 Average arrival length of 35,6 m1
Staff:	2 staff members present 2 extra staff members with an arrival time of 240 s 4 extra staff members with an arrival time of 360 s
Compare with:	Dutch Building Decree existing buildings Without permanent surveillance

Table 7.1 Input values.

The following changes are made in the input to achieve a lower risk and shorter egress time;

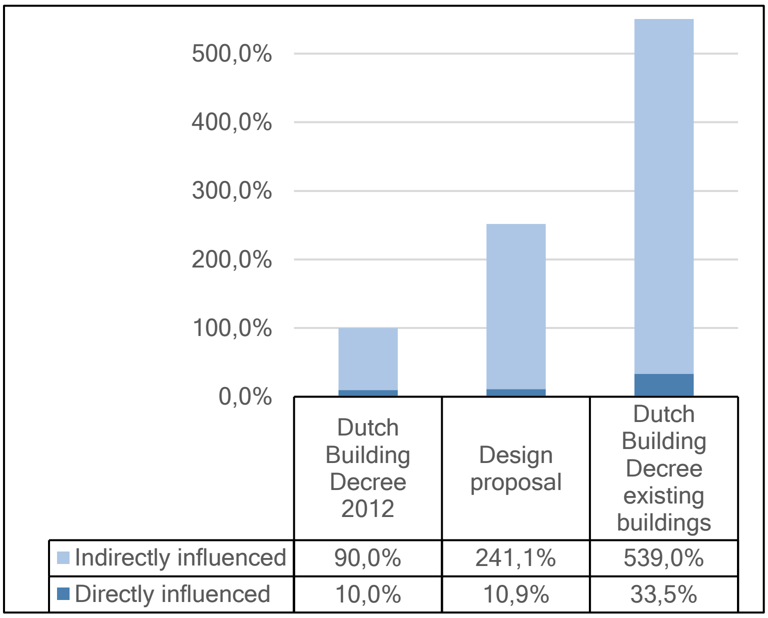
Design options:	Self closing doors patient rooms Material restrictions in corridor

Table 7.2 Input values.

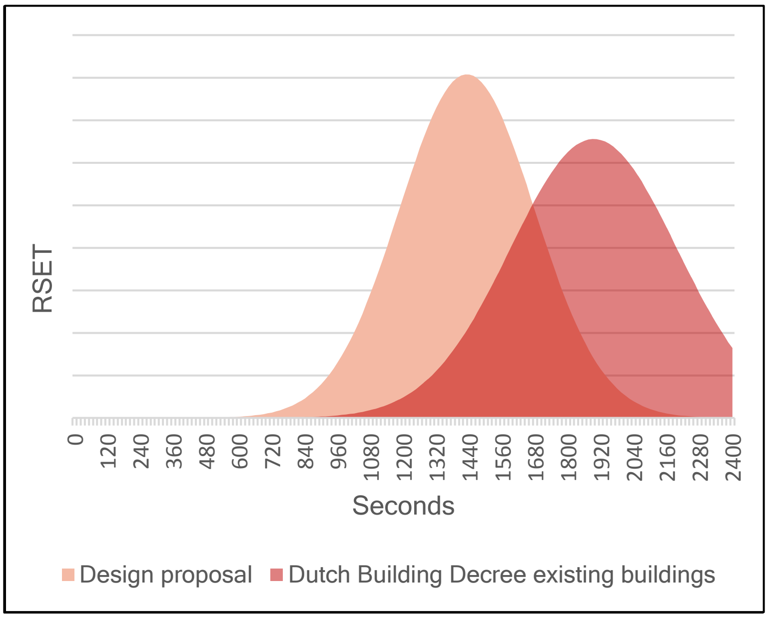
To achieve a level of safety which can be compared with the regulations of new buildings more changes are required. It seems the best option to split the compartment up with an extra separation. The results are placed in graph 7.5 and 7.6. The following input is necessary;

Surfaces:	3 patient rooms of 6 persons of 50 m2 6 single patient rooms of 13,5 m2 Auxiliary rooms of 157,6 m2. Corridor of 156 m2
Evacuation:	Standard patients Average evacuation length of 27,0 m1 Average arrival length of 32,0 m1
Staff:	2 staff members present 2 extra staff members with an arrival time of 240 s 4 extra staff members with an arrival time of 360 s
Compare with:	Dutch Building Decree 2012 Without permanent surveillance
Design options:	Self closing doors patient rooms

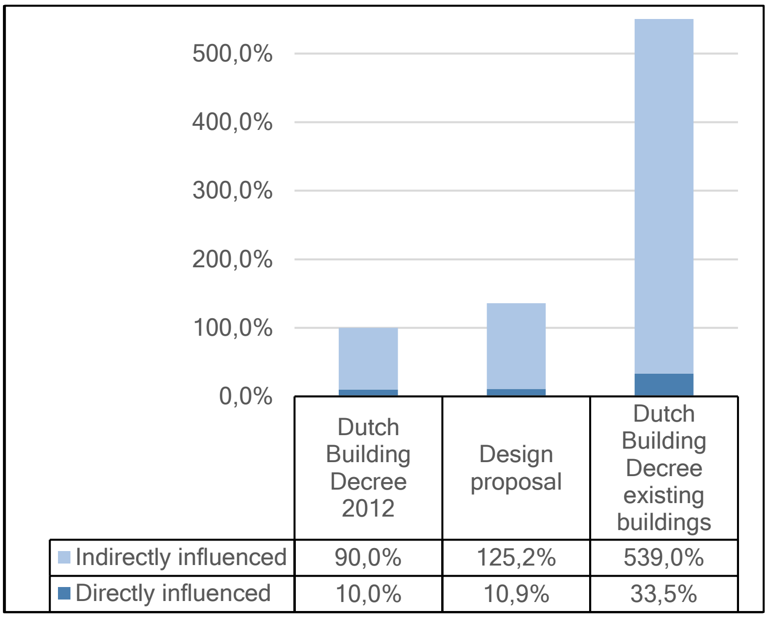
Table 7.3 Input values.



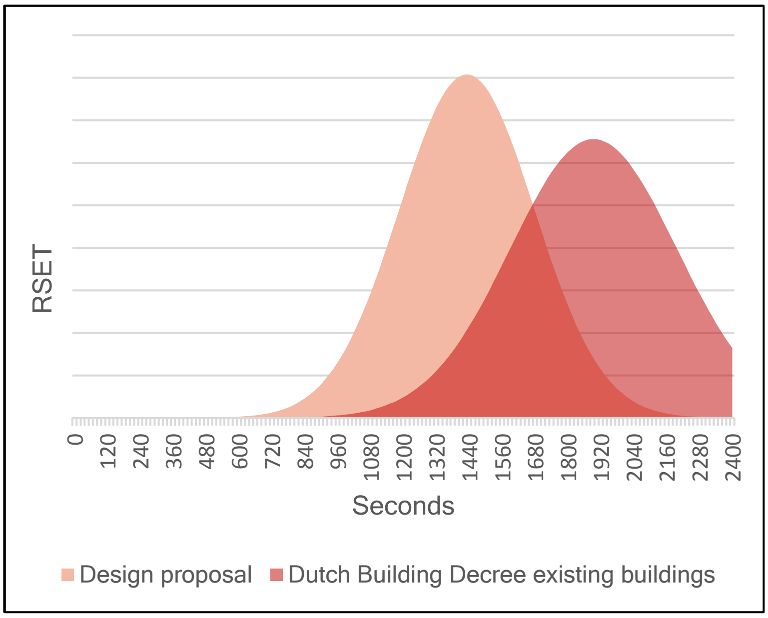
Graph 7.1 Probability of casualties of design proposal compared with Dutch Building Decree.



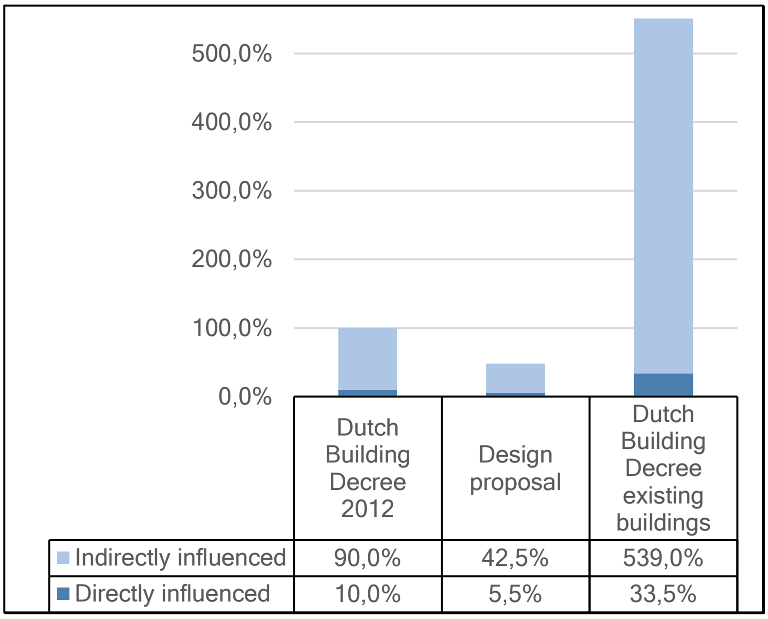
Graph 7.2 RSET of ward with standard patients.



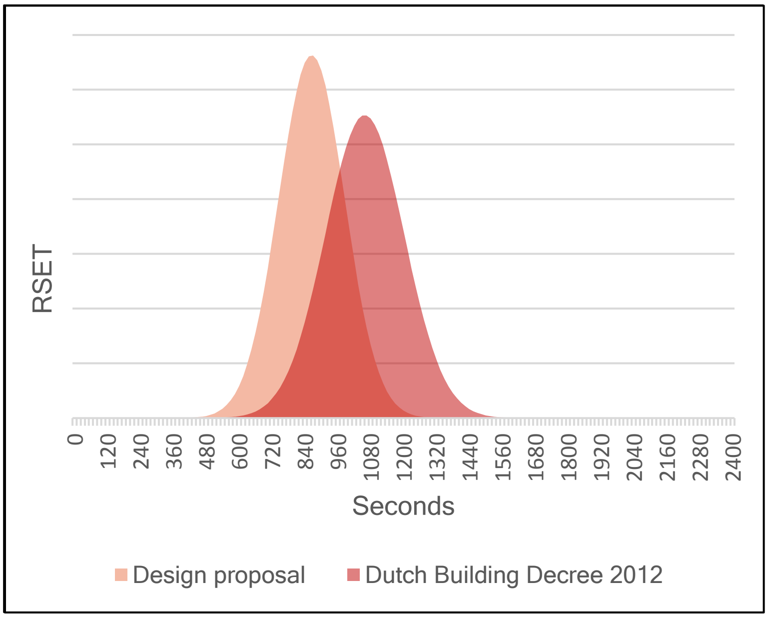
Graph 7.3 Probability of casualties of design proposal compared with Dutch Building Decree.



Graph 7.4 RSET of ward with standard patients.



Graph 7.5 Probability of casualties of design proposal compared with Dutch Building Decree.



Graph 7.6 RSET of ward with standard patients.

New designed hospital ward

The layout is based on a ward with only single patient rooms and a wider corridor, following the new architectural design trends. To be able to have 16 single patient rooms on the ward, the fire compartment is 654 m2.

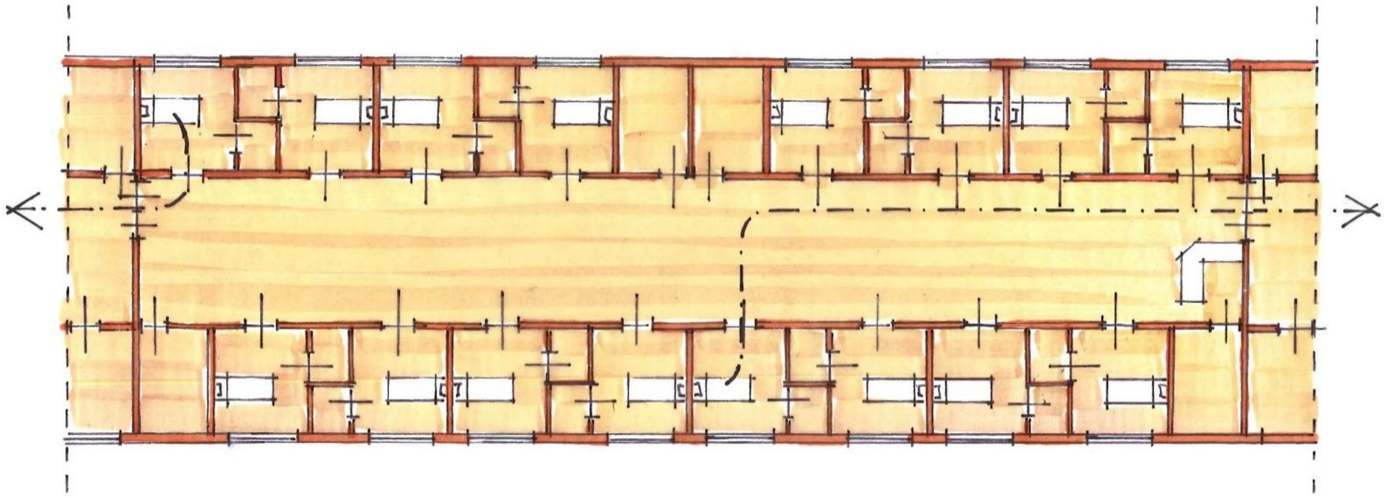


Figure 7.2 Proposed layout of regular patient ward following new design trends.

The input values of the design proposal are;

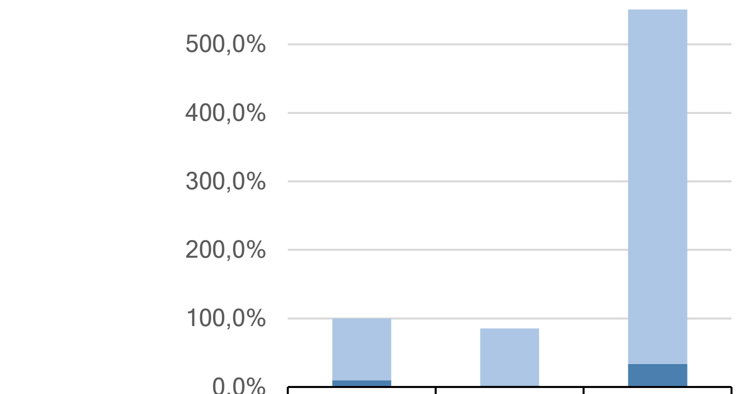
Surfaces:	16 single patient rooms of 21,25 m2 Auxiliary rooms of 49,5 m2. Open corridor of 265,5 m2
Evacuation:	Standard patients Average evacuation length of 18,5 m1 Average arrival length of 21,9 m1
Staff:	2 staff members present 2 extra staff members with an arrival time of 240 s,
Compare with:	Dutch Building Decree 2012 Without permanent surveillance

Table 7.4 Input values.

The following changes are made in the input to achieve a lower risk and shorter egress time;

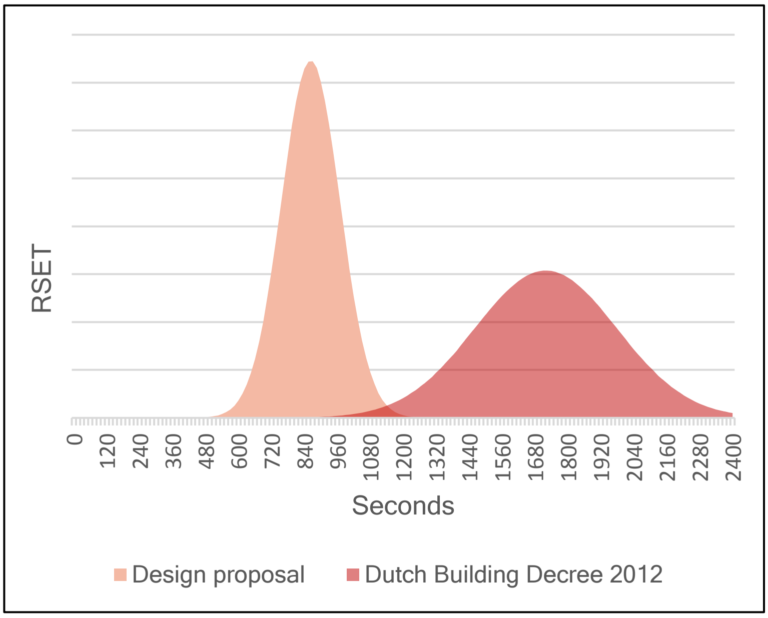
Staff:	2 staff members present 2 extra staff members with an arrival time of 240 s, 4 extra staff members with an arrival time of 360 s,
Design options:	Sprinkler added

Table 7.5 Input values.

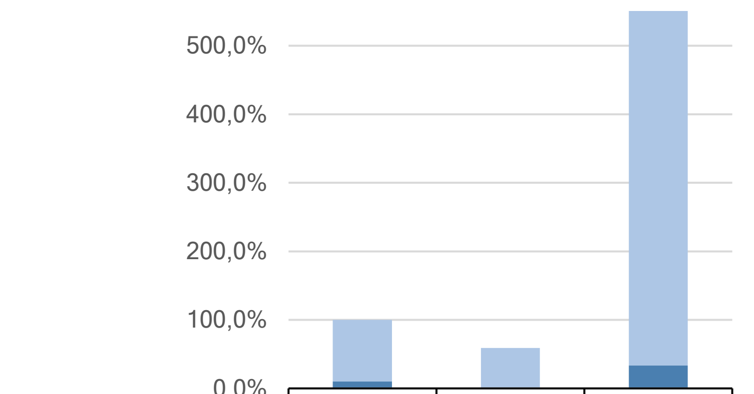


	Dutch Building Decree 2012	Design proposal	Dutch Building Decree existing buildings
Indirectly influenced	90,0%	83,5%	539,0%
Directly influenced	10,0%	1,8%	33,5%

Graph 7.7 Probability of casualties of design proposal compared with Dutch Building Decree.

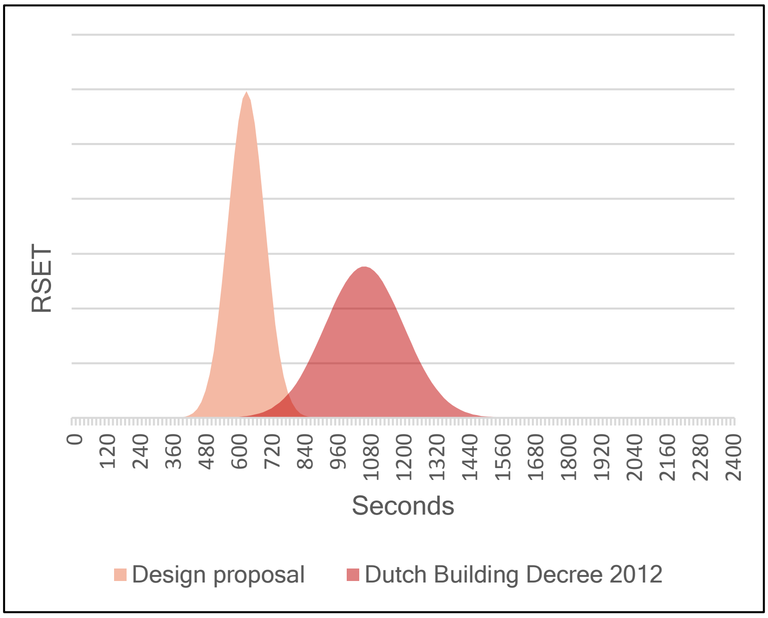


Graph 7.8 RSET of ward with standard patients.



	Dutch Building Decree 2012	Design proposal	Dutch Building Decree existing buildings
Indirectly influenced	90,0%	57,4%	539,0%
Directly influenced	10,0%	1,8%	33,5%

Graph 7.9 Probability of casualties of design proposal compared with Dutch Building Decree.



Graph 7.10 RSET of ward with standard patients.

Specific ward Intensive care

To get a feeling how the design tool works, and how it can be a usable while designing, two different types of cases are explained.

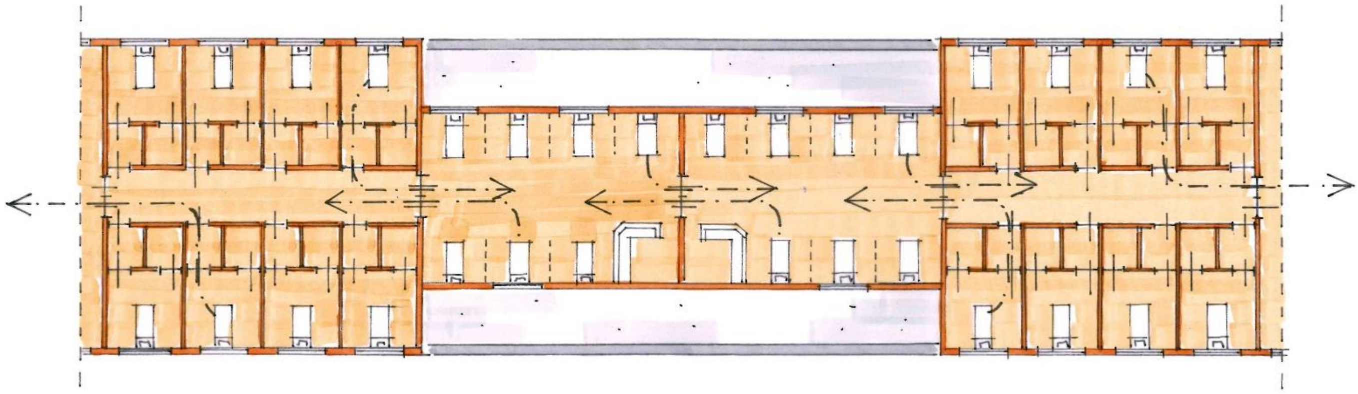


Figure 7.3 Proposed layout of Intensive care ward.

The input values of the design proposal of the open compartment are;

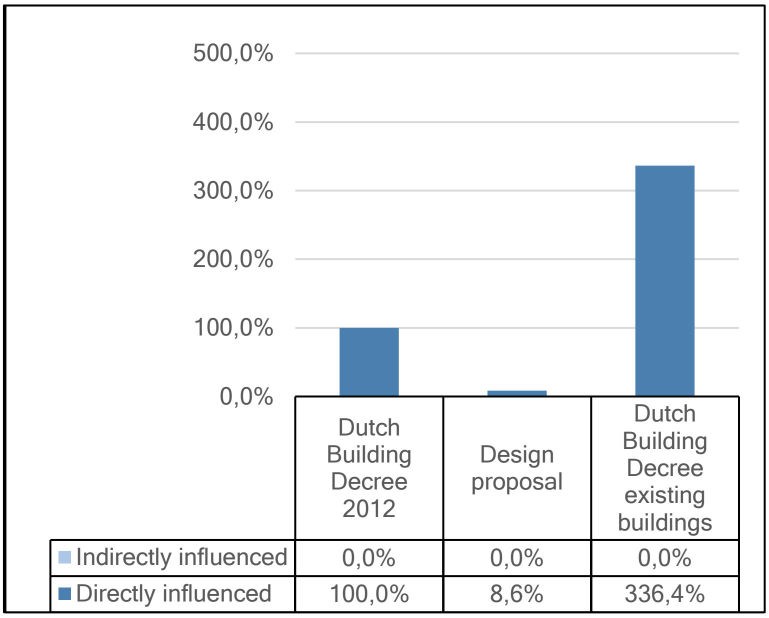
Surfaces:	Open space of 133,0 m2 with 7 patients
Evacuation:	Intensive care Average evacuation and arrival length of 10,2 m1
Staff:	2 staff members present 2 extra staff members with an arrival time of 240 s,
Compare with:	Dutch Building Decree 2012 Permanent surveillance

Table 7.6 Input values.

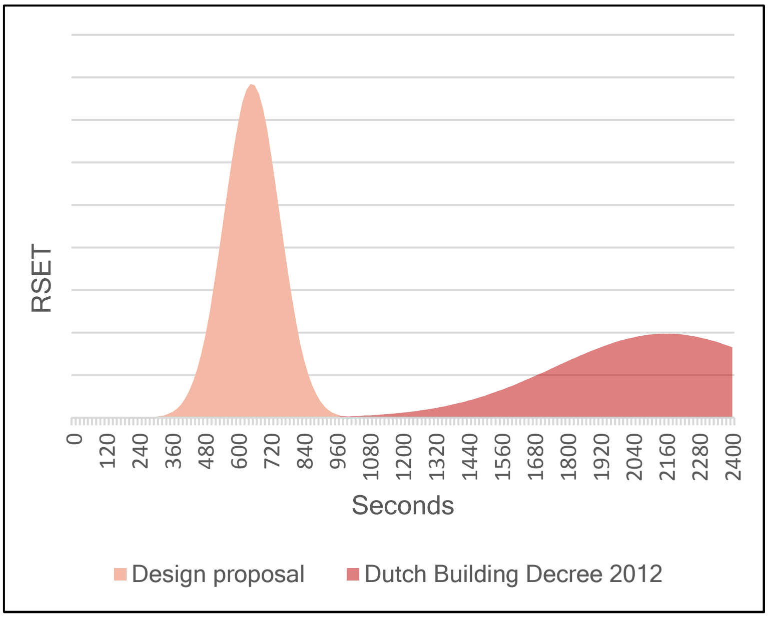
The input values of the design proposal of the compartment with single patient rooms are;

Surfaces:	8 single patient rooms of 29 m2 Auxiliary rooms of 49,5 m2. Corridor of 50 m2
Evacuation:	Intensive care Average evacuation length of 11,3 m1 Average arrival length of 14,1 m1
Staff:	2 staff members present 2 extra staff members with an arrival time of 240 s,
Compare with:	Dutch Building Decree 2012 Without permanent surveillance
Design options:	Self closing doors

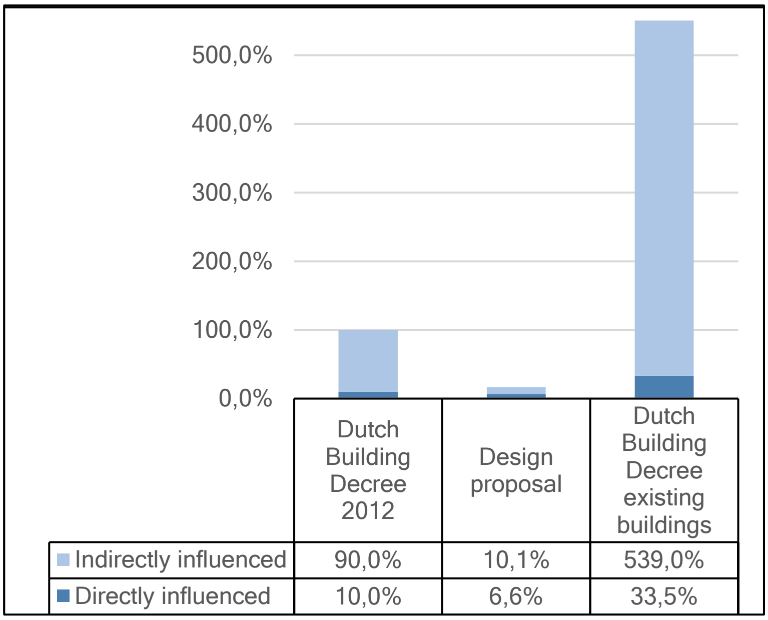
Table 7.7 Input values.



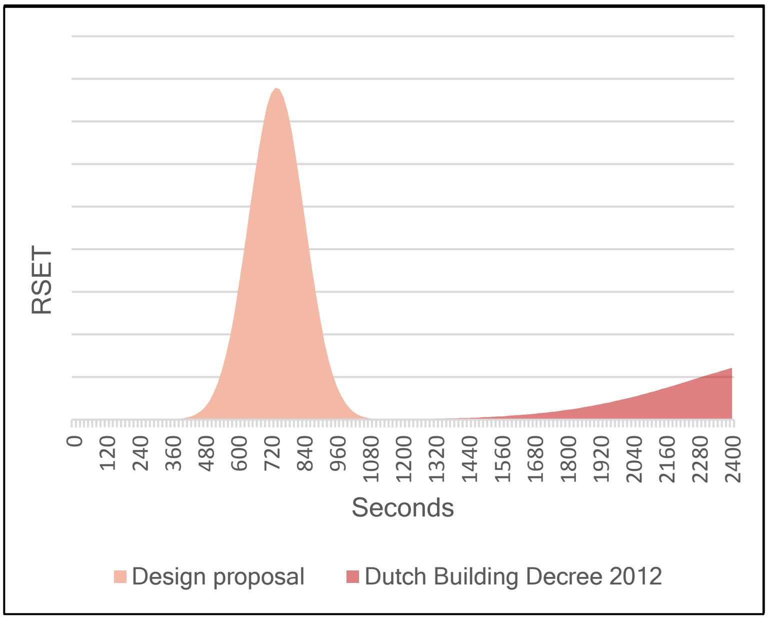
Graph 7.11 Probability of casualties of design proposal compared with Dutch Building Decree.



Graph 7.12 RSET of ward with Intensive care patients.



Graph 7.13 Probability of casualties of design proposal compared with Dutch Building Decree.



Graph 7.14 RSET of ward with Intensive care patients.

Results

	Surface	Patients	Relative risk indirectly infl.	Relative risk directly infl.	Avg. RSET
Regular ward	750 m2	46	241,1%	10,9%	23:52 [mm:ss]
Regular ward with improvements	750 m2	46	125,5%	10,9%	23:52 [mm:ss]
Regular ward with smaller compartment	334 m2	24	42,5%	5,5%	14:25 [mm:ss]

Table 7.8 Results regular ward.

	Surface	Patients	Relative risk indirectly infl.	Relative risk directly infl.	Avg. RSET
New designed ward	654 m2	16	83,5%	1,8%	14:23 [mm:ss]
New designed ward with improvements	654 m2	16	57,4%	1,8%	10:29 [mm:ss]

Table 7.9 Results new designed ward.

	Surface	Patients	Relative risk indirectly infl.	Relative risk directly infl.	Avg. RSET
Intensive Care open part	133 m2	7	0,0%	8,6%	10:50 [mm:ss]
Intensive care with single patient rooms	282 m2	8	10,1%	6,6%	12:20 [mm:ss]

Table 7.10 Results Intensive Care.

The regular ward in existing hospitals shows that the relative risk is high compared to the level of new buildings, and the required egress time is long. If hospital have an ambition to a certain level of safety they want to achieve, calculating and improving the building and the organisation of the staff can help them to choose the most ideal solution. Different options can easily be compared, because the tool gives clear results.

The second and third design case gives insight in how new designs can be structured regarding the fire safety and safe evacuation. Designs should be adapted to the actual use and the actual total egress time of the ward. With the tool, it is possible to estimate the risks and the egress time, and change or improve the designs.

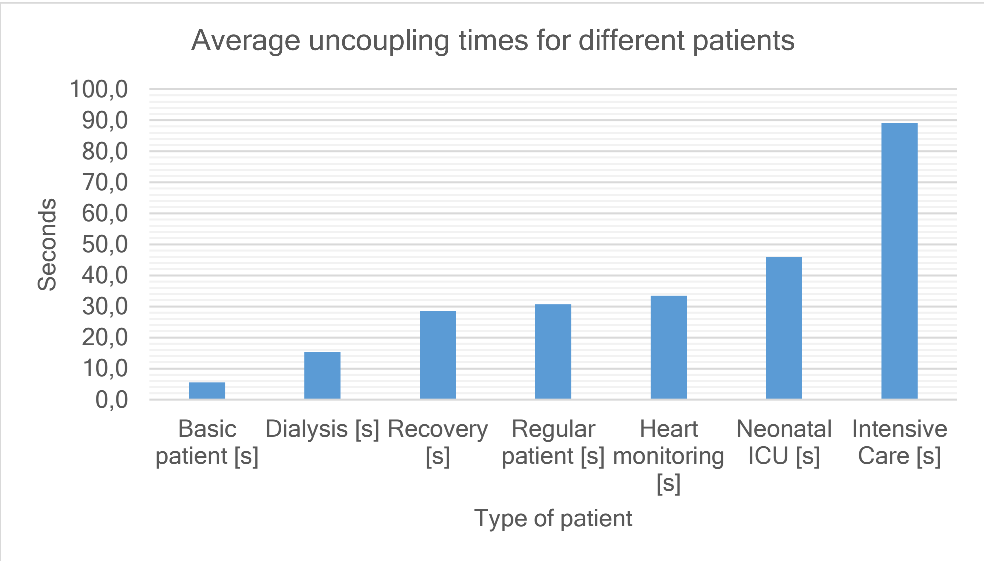
8. CONCLUSIONS & RECOMMENDATIONS

Looking back on the main research question, a design tool for an integrated fire safety concept is created. In this design tool, different parameters have been applied. It is possible to calculate for different types of hospital wards the actual fire risk of a design. When a fire occurs, material choices, fire safety installations such as a sprinkler but also self-closing doors and the behaviour of staff makes a difference. The actual use in hospitals can be considered. With the research, data has been gathered on evacuation times of specific patients. These times can be considered in designing different types of wards.

Experiments

An important part of the research was to get more insight in the differences of uncoupling and evacuating times of different types of patients. By performing literature research some evacuating times could be included in the design tool to calculate egress times for total hospital wards. But to be able to make detailed designs for hospital wards, defined uncoupling times have been gathered. The results of different uncoupling times of the research performed are displayed in graph 8.1

The results show that there is a big difference in the uncoupling times between certain wards. This uncoupling time will have a big influence on the total egress time of a ward, especially when multiple patients are present in one fire compartment. The actual uncoupling time and total evacuation time per patient should be considered in designing hospital wards.



Graph 8.1 Average uncoupling times per patient on specific wards.

Experiments of evacuating a complete standard hospital ward gave more insight in the actual behaviour of staff, and important observations of influences on the required egress time of a ward. Delay in the evacuation can occur if staff doesn't exactly know what to do, and time is lost in coordination consultation between the staff members. When there is confusion about the order of evacuating the bedridden patients, extra staff who arrives will need time to discuss to see which patients or actions of the evacuation still need to be executed. Behaviour of patients can also have a counteracting effect on the evacuation time.

Design

With a more integrated approach sufficiently safer hospital wards can be designed. Using the design tool will help designers and the board of directors of hospitals to find the balance between the level of safety and the level of staff they want to establish, and the related cost of the different options and staff. With the design tool all types of layouts can be created. With the probability approach, actual risks can be determined. And with the gathered data the RSET of a ward can be determined. The design for different hospital wards with this approach can be more flexible and integrated, compared with the current regulations that are basically focused on demands about the maximum allowable square meters. With the design tool, easily a balance can be made between desired safety level and the related cost.

The design tool calculates a relative risk of casualties per design of a ward, which fits in a fire compartment. With adding different probabilities, the risk value can be determined. In the design process, it is possible to change or add probabilities, such as adding self-closing doors or a sprinkler installation to the design. These parameters will decrease the actual risk on casualties on ward.

With the data gathered a specified RSET can be calculated for specific wards in the hospital. By comparing the calculated evacuation time with a hospital ward based on the current regulations as well, the effects of choices both in the design but also in the number of staff present to full fill an evacuation can be displayed. How faster an evacuation can be successful proceed, the lower the chance on casualties. However, it is a requirement that staff in hospitals has already achieved a certain training level to proceed fast evacuations. When the staff is already trained the calculated RSET can be achieved.

Although there is no option for the most efficient safe design per hospital ward there are different options to optimize the risk value. With different design options, it is possible to decrease the risks and changes in the presence of staff that can perform an evacuation. A combination of solutions can create an acceptable risk per hospital ward. Hospitals need to decide in the design process if the risk based on the current regulations is acceptable, or that a higher level of safety needs to be achieved. With every parameter that will give different costs, hospitals are free to choose which set of parameters will be the most efficient.

Approaching the fire safety in hospitals with a more flexible design strategy, hospitals have more freedom in designs for different types of wards, and the effectivity of the measures they choose to reduce the risk. With directly implanting the number of staff members who can proceed an evacuation and their arrival time in the design, the desired connection between adjustment on the building and the organisation of staff is made. Hospitals can make a financial consideration between investing in adjustments on the building level, or choose to invest more in staff support.

Recommendations

Further research can focus on gathering more data about uncoupling times of specific patients. More gathered data will be necessary to have a more reliable average values the evacuating times. The standard deviation of a RSET calculation can be defined more precise when more research will be performed.
Also, other parts of the evacuation route can be further investigated. There can be differences in leaving different types of patient rooms, and passing different types of fire compartment separations.

To create a more on risks focused approach for hospital designs more research will be necessary. Data about the causes of fires is necessary, and more insight in the number of fires and the consequences. Not only data need to be gathered about large fires with casualties, but also small fires which are self-extinguishing or are extinguished by staff. With this wider spectrum of data and knowledge an actual estimation about the chances of a fire can be made, and the chance when a fire can lead to evacuation of a part or the entire hospital. When there is more data available of fires on different types of hospital wards, it would be possible to calculate the actual risk per patient with the design tool.

The created design tool focuses now on calculating the relative risk on casualties per design of ward. Besides this, the total Required Safe Egress Time including standard deviation has been calculated. Decreasing both values will lead to safer designs. But both values need to be interpreted individually. More research and data about the chance of fire occurring in hospitals and the fire growth of fires in hospitals are required, to be able to combine both values to create one overall risk valuation for new designs. With a combined value a more validated consideration can be made on financial level.

Evacuation procedures in hospitals should be kept simple for staff. A fire emergency in a hospital shall always be a rare incident. Therefore, the choices staff must make to proceed a successful evacuation must kept simple and in a logical order. Focussing on a successful extinguish attempt can be a solution to make all the hospitals sufficiently safer. Staff must be trained in proceeding evacuations as fast as possible, with special attention to make sure that all separation doors will be closed.

Designs for hospital must be in such a way that it is almost always possible to evacuate a bedridden patient in two directions. Research showed that the chance on a successful evacuation decreases significantly if patients must be evacuated via the stairs. If it is the strategy to evacuate all patients in bed, it is important that an evacuation can be proceeded fast without large deviations. Designs of hospitals must be in such a way that there is always enough holding capacity for all patients in bed in the next fire compartments.

9. REFLECTION

When I started the research, I didn't have much knowledge about fire safety and the effects of a fire safety approach for the design of buildings. The first step was to gain understanding of the subject. This was done by searching literature on fire safety and searching for information about (newer designed), and the effect of the current regulations as stated in the Dutch Building Decree for designs of hospitals. In this phase the question arises more and more if it is possible to find a more integrated approach that matches the real fire safety problems that are currently present in hospitals.

Approach

One of the objectives of the research was to categorise data from egress times for different types of patients. After literature research, I could not find existing data about the egress times of different types of patients. Experiments in real hospitals were required.

By recording an evacuation drill of an entire ward in an older hospital a lot of knowledge and data about the behaviour of staff could be gathered. The most important observation was that the level of trained staff is very important for the required egress time of a ward. The recordings also showed that when there was only one exit on a hospital ward that can be used for evacuation of beds, the required egress time increases a lot. If the bedridden patients need to be evacuated by using a movement device for evacuation on stairs, a successful evacuation seems to be unreachable. The recorded evacuation drill showed that when staff is not trained, the times found in already researched data are impossible to accomplish. The evacuation drills showed that if there is a fire in the corridor area, a successful evacuation is in danger and likely to be impossible.

The evacuation drills performed in the second hospital are more focused on purely getting data of egress times of specific hospital wards. The experiments where stricter to one evacuation route, or evacuating one patient multiple times out of the same patient room. For this reason, the experiments could be better used to define average data for the different parts of the evacuation process.

Another objective of the research is to develop a design tool that can help designers to design safer hospitals. Using the probability approach in combination with a verified egress time of the entire ward, a calculated effect can be determined. Different options for the design can be implemented in the probability calculation, and will therefore influence the value that marks the level of fire safety of the layout. The options for designers will be much wider, and more options will be available, that can improve the awareness of fire safety, and makes the hospitals sufficiently safer.

Research & Design

The aim of the research is to be able to create design guidelines for state of the art fire safety concepts for hospitals. The design trends, actual use and corresponding egress time need to be integrated in the guidelines. With the gathered data, an RSET per specific hospital ward can be determined and calculated. With this determined RSET the actual use of a ward can be analysed. The number of staff present is important for the RSET, and can be customised to get a smaller relative probability of casualties.

By creating a basic value for the probability of casualties of a layout that fulfils the current Dutch Building Decree regulations, wards with an entirely different layout can be compared on the level of fire safety. Therefore, new design trends can be designed which are not only focussing on complying with the regulations which are focussed on maximum allowable square metres. New designs can follow the probability approach to determine a value that can be significantly safer.

This approach can also help existing hospitals with less efficient layouts for fire safety, to secure a certain percentage of safety for bedridden patients. Adjustments to the building can be made, to have a lower relative probability of casualties. But when investing in a building isn’t an option, making sure a better level of trained staff is achieved, can help decreasing the chance of a developed fire. It can also help to make improvements to decrease the RSET, with better planning of extra staff arriving when an emergency occurs, or better trained so an evacuation can be executed faster. With this approach hospitals, can choose for example to improve in the organisation to decrease the RSET. With these improvements, the building can be sustained on an acceptable risk, instead of renovating or building a new hospital. The approach of the design tool gives options to make both new build and older hospitals tool to achieve an acceptable risk regarding the fire safety.

Improvements to the design tool could be made to link the chance of an occurring fire, more to the required egress time. In the scope of my research I was not able to link both these factors, to create one value per design. More research into data about fires in hospitals and egress times in different scenarios will be necessary.

With the graduation process coming to an end, I can say I gained a lot of knowledge about the fire safety approach in buildings with a complex design and comprehensive organisation. By thinking of designs for hospital wards on a different approach, it gave me knowledge how to implement the technology of fire strategies in the design process. By doing this research my interest in the fire safety engineering growth, and I would like to learn more about the topic in my further career.

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List of abbreviations

ASET	Available Safe Egress Time
RSET	Required Safe Egress Time
Neonatal ICU	An intensive care unit specializing in the care of ill or premature new born infants
SHEVS	Smoke and Heat Exhaust Ventilation System
WBDBO	Resistance to fire penetration and spread
DBD	Dutch Building Decree (Bouwbesluit 2012)

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10. APPENDIX

Appendix

In the appendix is included;

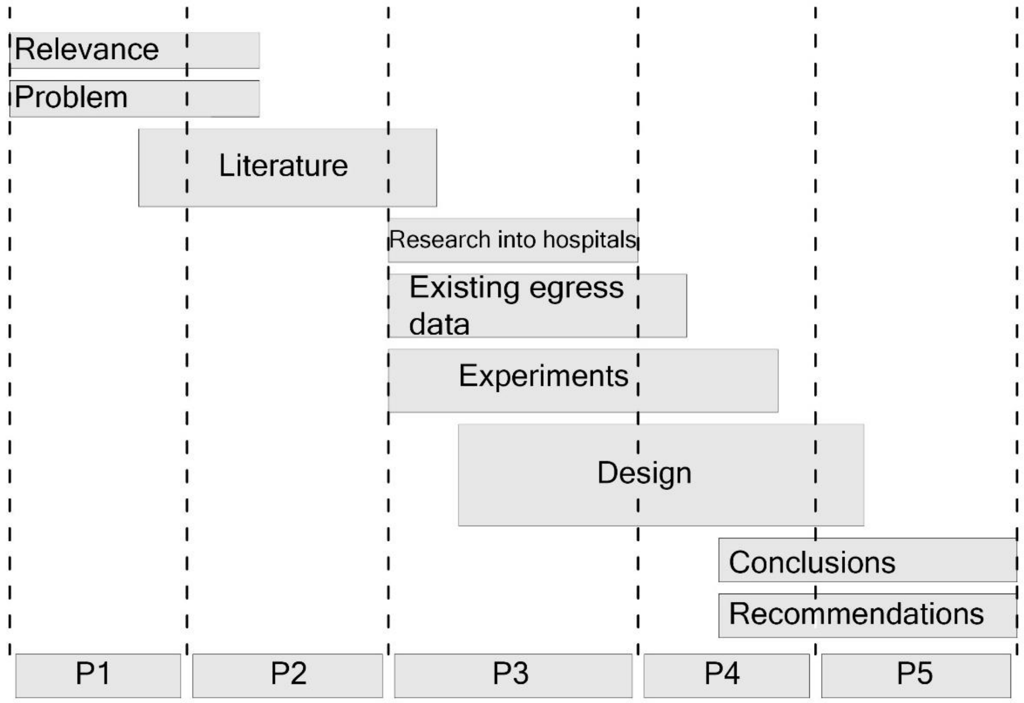
- Planning of the research
- Analysis of hospitals
- Extra egress data
- Overview of existing egress data
- Copy of the input screen of the design tool
- Design concepts
    - Regular hospital wards
    - Hospital ward with stairs
    - Specific wards

Planning

The research will be approached in different phases. After the relevance is described, and the problem is stated, a literature exploration will be done into the changing design trends. From here different fire risks and current Dutch and International healthcare regulations will be analysed. The research and exploratory stage shall be completed before P2.

After this first phase the focus of the research will change to collecting already existing egress date of research done before, or data gathered by hospitals by performing fire drills. Part of the research will be experiments where fire drills are carried out and where various duration times will be measured.

The last part of the research will be creating a design tool with possibilities and solutions regarding the gathered egress time. The aim is to design layouts with a more integrated fire safety approach, focusing on fire spread and compartmentation, to decrease damage and casualties. With these design proposals, an assumption can be made whether the Dutch building regulations regarding fire safety are sufficient, or if they should be altered and focused more towards integrated solutions.



Planning of research approach.

Analysis of hospitals

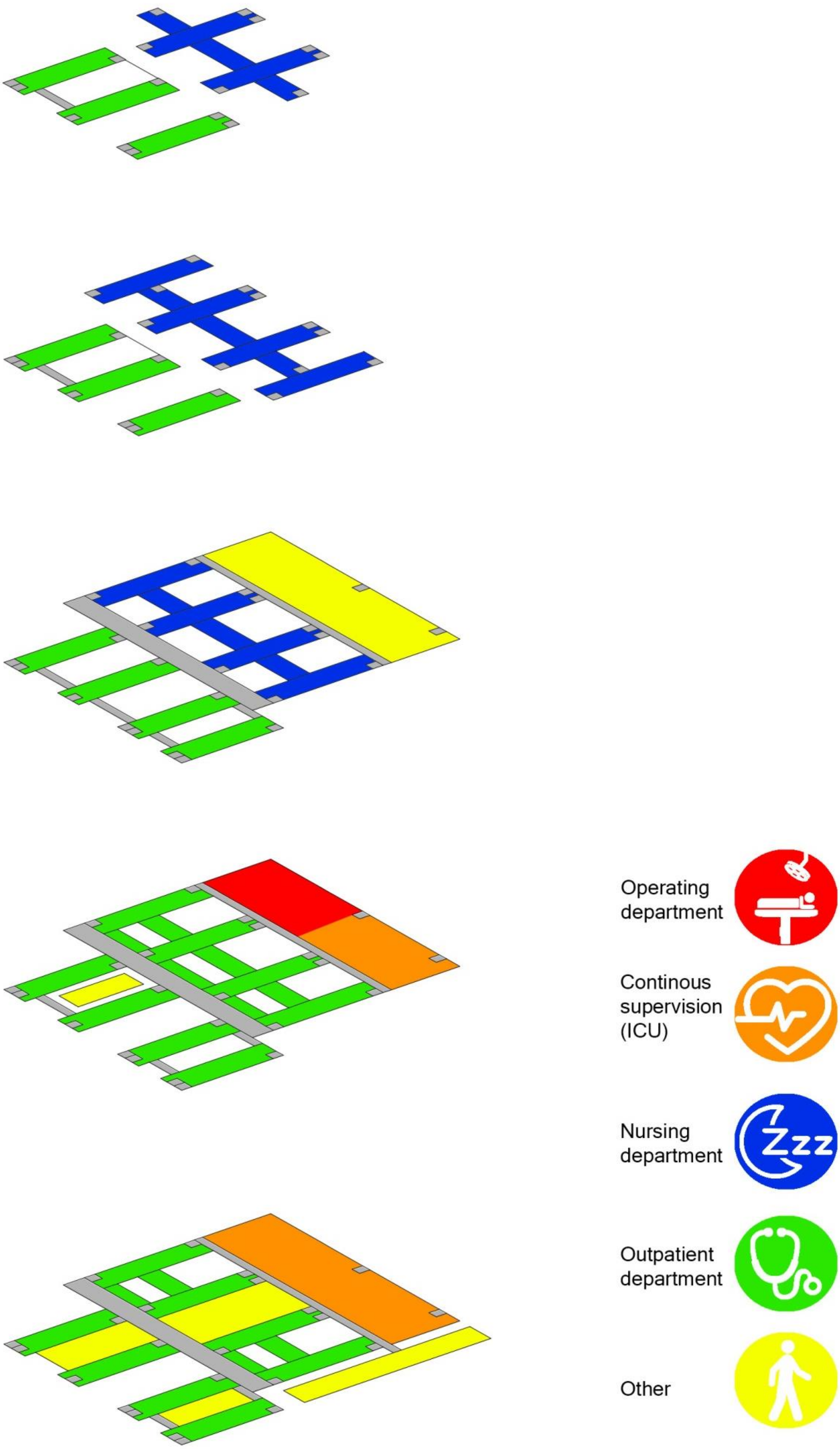
To get an idea of the compositions and layout for both recently designed and older hospitals, an analysis of typical wards in hospitals and positioning of stairs and elevators has been made. The analysis is visualised in the following figures.

In the analysis for the order of wards in hospitals, a classification is made. Wards are split up in operating departments, where the operating theatres but also supporting functions for the department are. Wards with continuous supervision, such as an ICU, but also a recovery or Neonatal ICU. The wards classified as nursing departments are the regular nursing wards, where the staff: patient ratio is varying. On these wards have less staff available per patient compared to wards with continuous supervision.

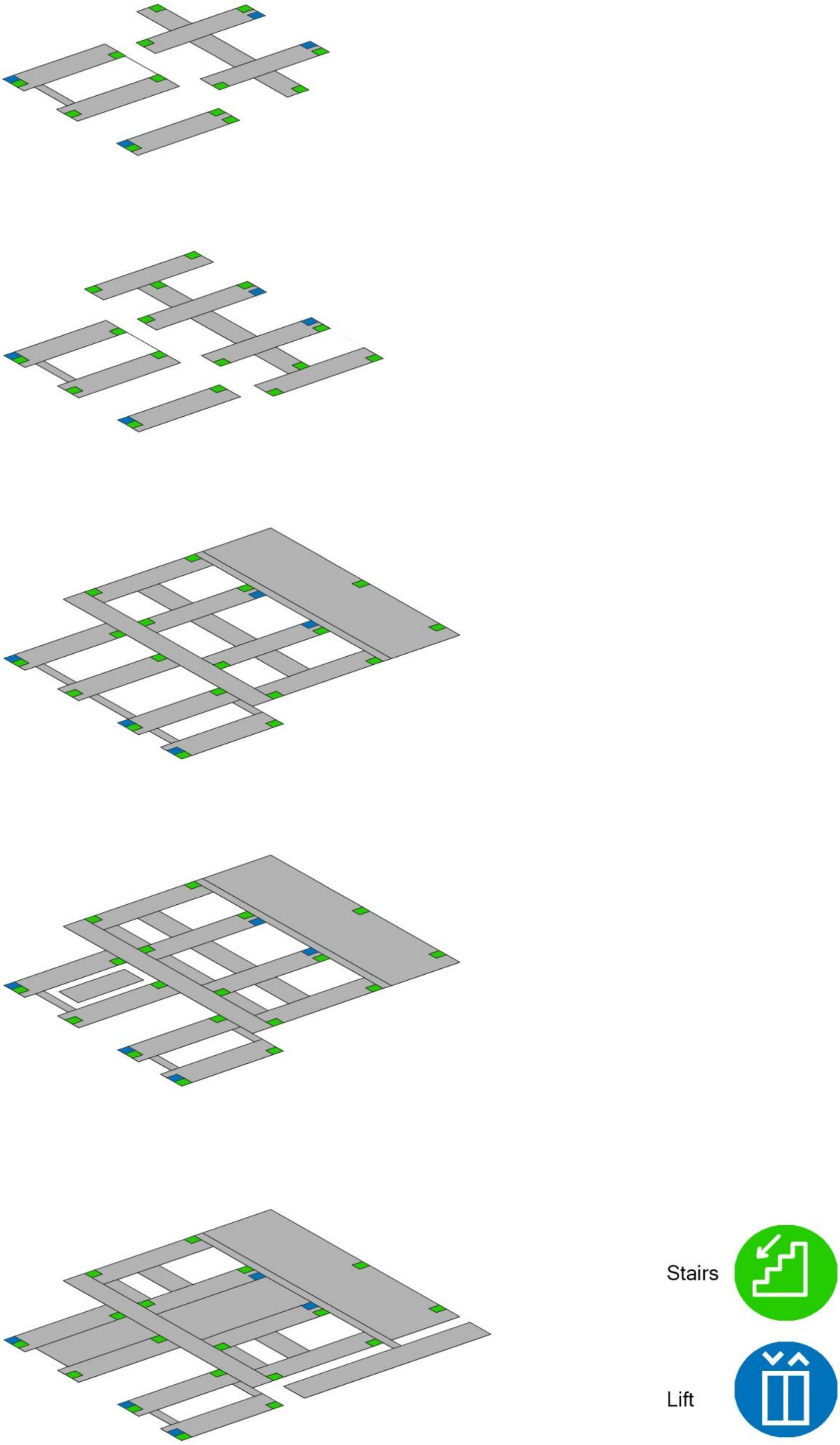
Parts of hospitals specified as treatment areas are for example outpatient clinics where patients visit a doctor. As patients do not stay long in these wards, this condition must be considered during analysis in these areas of the hospital. In these areas no patients are likely to be a sleep.

The areas marked as other are for example rooms for facility or areas where only staff are allowed. It is possible to speculate that these areas will not consist of vulnerable people who are not self-reliant in case of evacuation, or can't be directly assisted if necessary. Areas such as a restaurant are marked as other. It is likely that vulnerable people in these areas will also be in the company of self-reliant people. Since these people already moved from their ward to the general parts of the hospital, no disconnecting will be necessary to move to another part or outside the hospital.

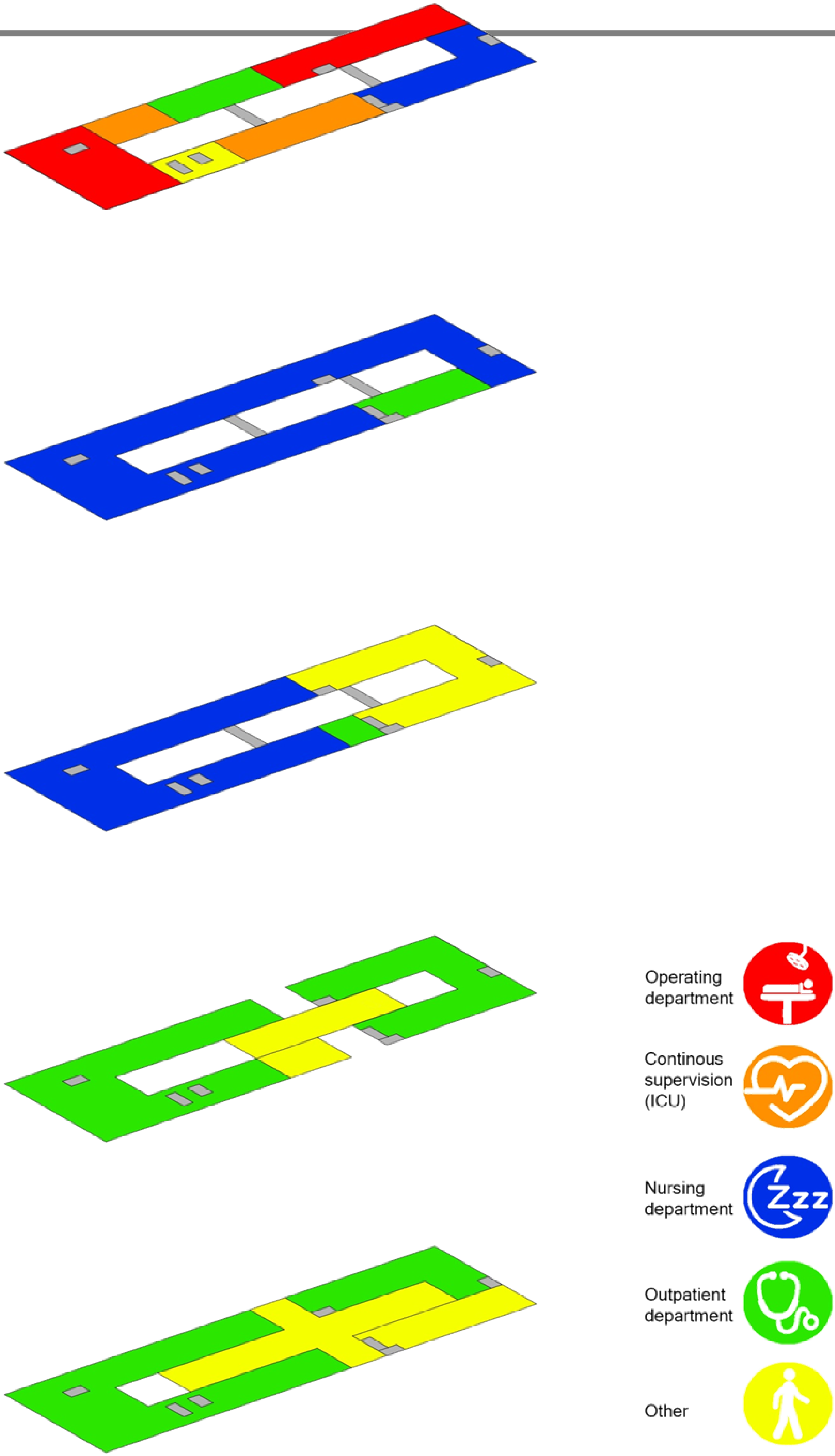
The second part of the analysis of the hospitals is important for vertical transportation, from floor to floor. Therefore the stairs and elevators can be used. In the analysis, no differentiation has been made between elevators that can be used during an emergency and those that cannot be used. The common strategy for hospitals is that elevators close to the emergency alert cannot be used for transportation of patients, but will be claimed by firefighters.



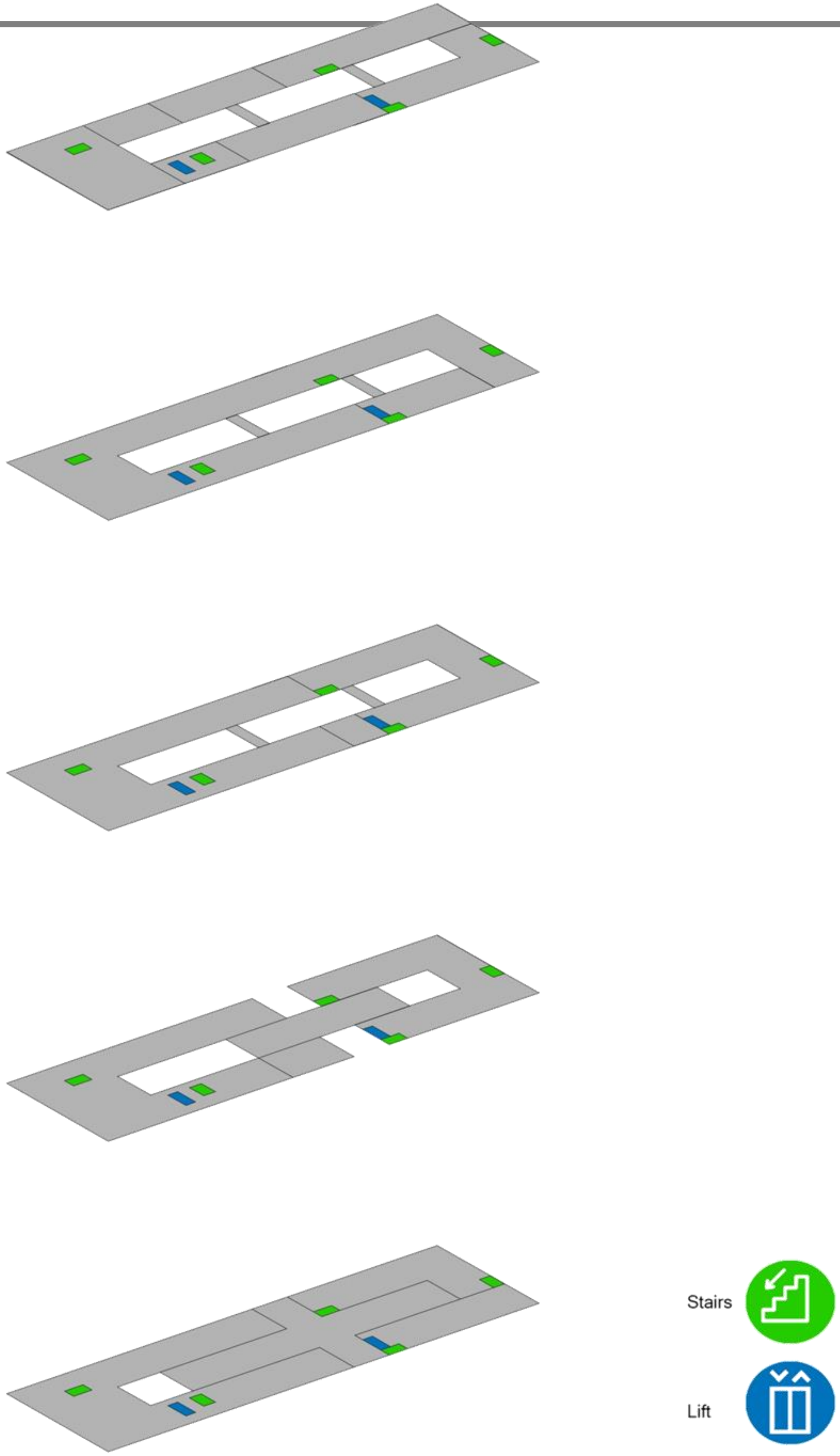
Typical wards in recent designed hospital



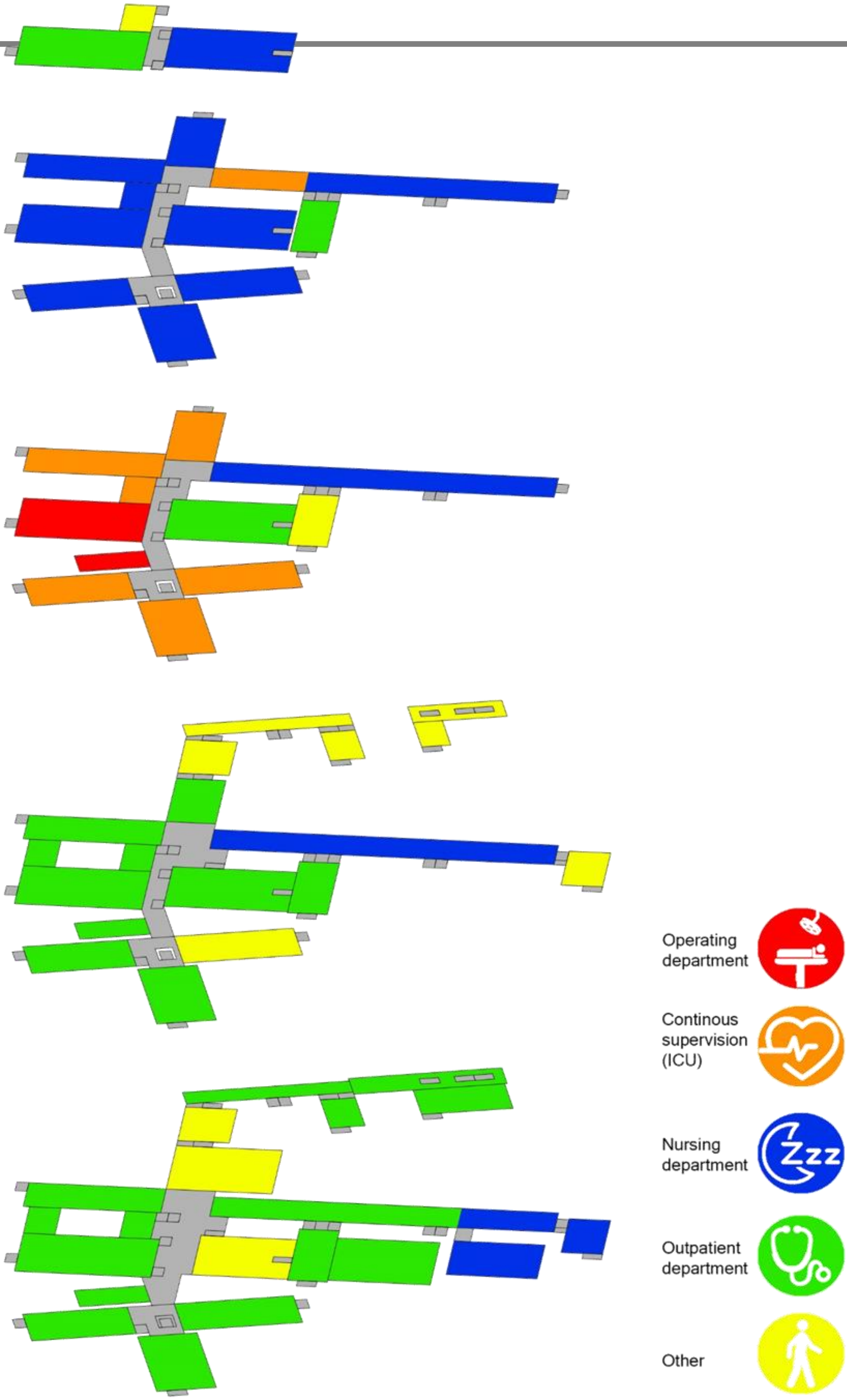
Stairs and lifts in recent designed hospital



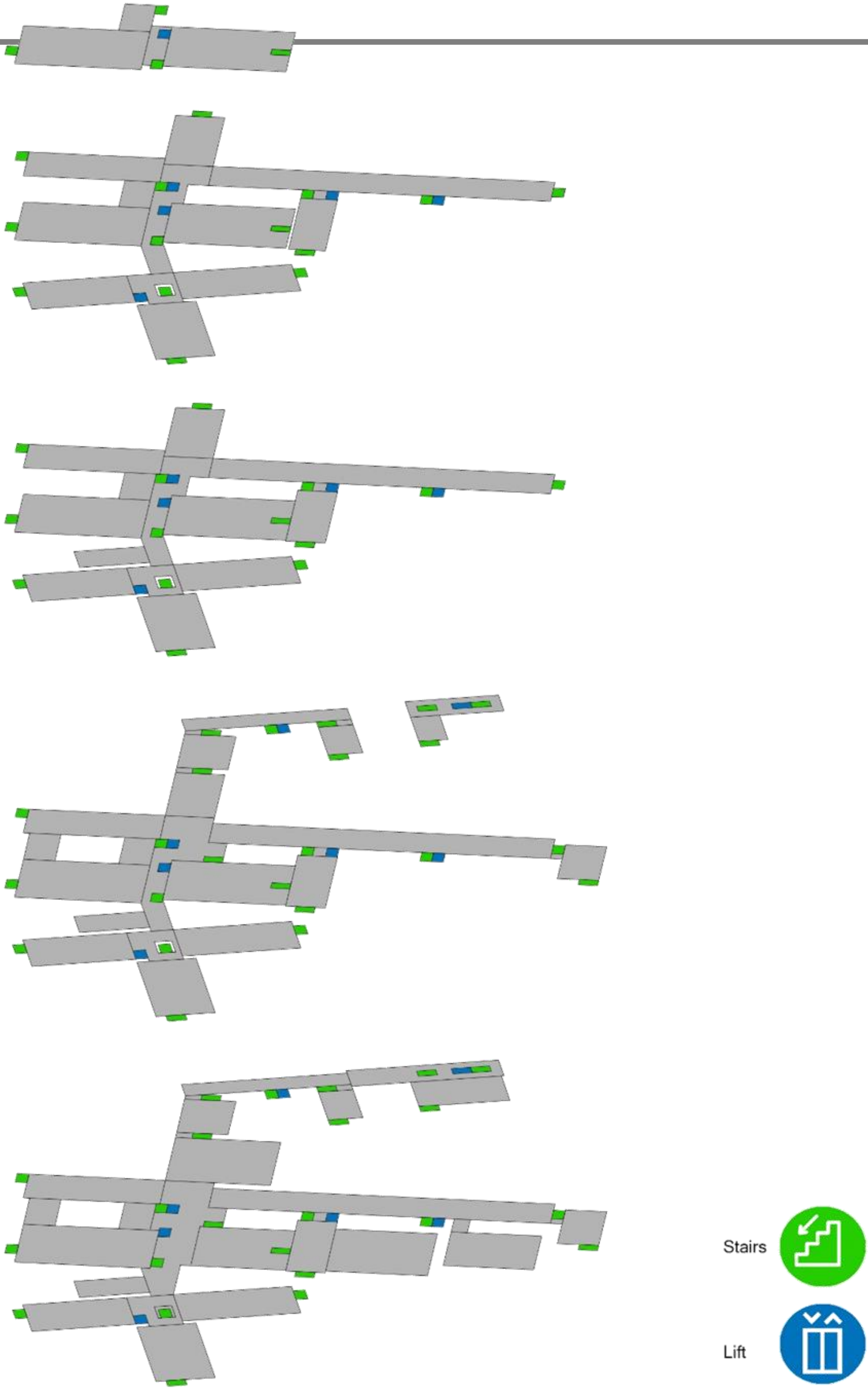
Typical wards in recent designed hospital



Stairs and lifts in recent designed hospital



Typical wards in older hospital



Stairs and lifts in older hospital

Bedridden patients in specific hospital wards

Specific egress times are measured for some hospital wards. The egress times displayed are recorded from videos of performed evacuation drills in hospitals. Whilst the data has only been recorded once or few times, it gives an indication to the difference in evacuation of patients in specific wards. Further research will be necessary to have valid egress times for specific wards so an integrated strategy can be designed.

Recorded times for both wards are from one fire drill, with the assistance of two staff members. Both patients were connected to different medical equipment. The patient on the hospital ward surgery is connected to an infusion, epidural, feeding tube, oxygen flow meter, vacuum and a catheter. The patient that was evacuated from the internal medicine ward was connected to a feeding tube, non-rebreathing mask, syringe pump, infusion and a catheter.

Type of ward	Uncoupling time	Leaving room	Number of tests	Number of staff
Surgery	24 s.	13 s.	1	2
Internal medicine	54 s.	10 s.	1	2

Table 1 Evacuation times of specific hospital ward.

There is also some data available about egress times of wards with heart monitoring and dialysis. Data of the heart monitoring ward is captured from one evacuation drill of the total ward, with six beds present. Only two beds were occupied by patients. On the ward, there were four single patient rooms, and one two patient room. The rooms had self-closing sliding doors. The evacuation drill of the ward was performed by three staff members.

On the Dialysis ward the staff disconnects the patient and evacuated them whilst in the hospital bed. A test was performed with people in beds. The patient rooms used were in open connection with the ward. Many beds and various equipment were present on the ward which had a negative affect on the evacuation speed.

Type of ward	Uncoupling time	Leaving room	Number of staff	Number of tests
Heart monitoring	20.5 s.	7.2 s.	1	6
Dialysis	25.0 s.	13 s.	2	2

Table 2 Evacuation times of specific hospital ward.

Data is captured from a recorded evacuation drill of a Neonatal ICU, where times could be derived of four total evacuations. For the drill staff is using mannequins to replace real patients. The evacuation is performed by three staff members in total. Two ‘patients’ are evacuated in a hospital crib, two other ‘patients’ are evacuated in the incubator, specified in the table as type 2. Both types required disconnecting of equipment.

Type of ward	Uncoupling time	Leaving room	Positioning	Number of staff	Number of tests
Neonatal ICU type 1	31.5 s.	13 s.	10 s.	1	2
Neonatal ICU type 2	26.7 s.	10 s.	30 s.	2	2

Table 3 Evacuation times of specific hospital ward.

For the most important wards for the design the research is gathered and performed. These wards are expected as the highest risk wards because of the combination between the staff-patient ratio and the uncoupling time of equipment per patient.

Self-reliant independency		Preparing/ uncoupling	Leaving room	Horizontal speed	Placing
		[ss](staff)	[ss](staff)	[m1/s](staff)	[ss](staff)
Staff	-	44,1	-	1.6	-
Self-reliant	-	50,8	-	1.6	-
Reduced self-reliant	No aid	-	-	0.95	-
	Crutches	-	-	0.94	-
	Walking stick	-	-	0.81	-
	Rollator	-	-	0.57	-
	Blind (assisted)	-	-	0.78 (1)	-
Seated evacuation	Wheelchair manual	-	-	0.69	-
	Wheelchair assisted	29,09 (2)	-	1.30 (1)	-
	Wheelchair electric	-	-	0.89	-
Bedridden I	One bed out of six patients room without uncoupling	-	12 (2)	-	-
	One bed out of six patients room with uncoupling	10.4 (2)	8.4 (2)	0.48 (2)	-
	One bed out of single patient room without uncoupling	-	11.25 (2)	-	-
	One bed out of single patient room with uncoupling	12 (2)	8.6 (2)	-	-
	One bed out of single patient room with uncoupling & oxygen flow meter	15.4 (2)	9.6 (x)	-	-
	Patient with uncoupling	8.59 (2)	-	0.88 (2)	8.11 (2)
Bedridden II	Intensive care	81.89 (2)	-	1.14 (2)	5.73 (2)
Bedridden III	Operating theatre	9:18 (8+)	?	?	?

Table 1 Egress data of horizontal evacuation

Self-reliant independency		Preparing	Horizontal speed	Speed on stairs
		[ss](staff)	[m1/s](staff)	[m1/s](staff)
Staff	-	0	1.6	0.8
Self-reliant	-	0	1.6	0.8
Reduced self-reliant	No aid	0	0.95	0.36
	Crutches	0	0.94	0.22
	Walking stick	0	0.81	0.32
	Rollator	0	0.57	0.16
	Blind (assisted)	0	0.78 (1)	0.26 (1)
Seated evacuation	Evacuation chair	33 (2)	1.46 (1)	0.83 (1)
	Carry chair	42 (2)	1.50 (1)	0,58 (4)
Bedridden I	Rescue sheet	65 (2)	0.89 (2)	0.67 (2)
	Stretcher	78 (2)	1.04 (4)	0,53 (4)

Table 2 Egress data of vertical evacuation

Design tool

Input screen and results of design tool

Design concepts

With the design tool for every lay out a risk of fire occurring can be determined. Beside the RSET with standard deviation can be calculated. The probability of a fire occurring and the RSET of a ward gives an indication on what the level of risk or safety is for the design of a hospital ward.

In the concepts two different types of hospital wards are calculated. The first type of ward that is calculated is a standard type of hospital ward, where regular patients are present. The second type of ward that is calculated are more specific types of ward. The RSET of these types of wards could be calculated with the experiments performed. Different variants of the standard hospital wards are added and calculated with the design tool, to show the differences the design tool creates.

In the second part calculations are made for more specified hospital wards, such as ward for Dialysis and Intensive Care. With the gathered data from the research RSET's for this types of wards could be calculated.

The RSET for the designs on the following pages are calculated with 2 staff members present on the ward. Assumed is that 2 staff members are present on the ward with an arrival time of 2 minutes. For the more specialised wards the calculations are made with 4 staff members present on the ward, and 2 extra staff members present on the ward with an arrival time of 2 minutes. 4 extra staff members present on the ward with an arrival time of 7 minutes.

Standard hospital wards

Dutch Building Decree

The layout is based on the maximum permissible values of the current Dutch Building Decree. The fire compartment is 500 m2 with 6 sub fire compartments as patient rooms of 50 m2. The patient rooms have a mandatory self-closing door.

The percentages calculated for this layout will be taken as basic value to compare with other layouts of standard hospital wards. The RSET calculations are made with 2 staff members present on the ward, and two extra staff members helping during evacuation with an arrival time of 2 minutes.

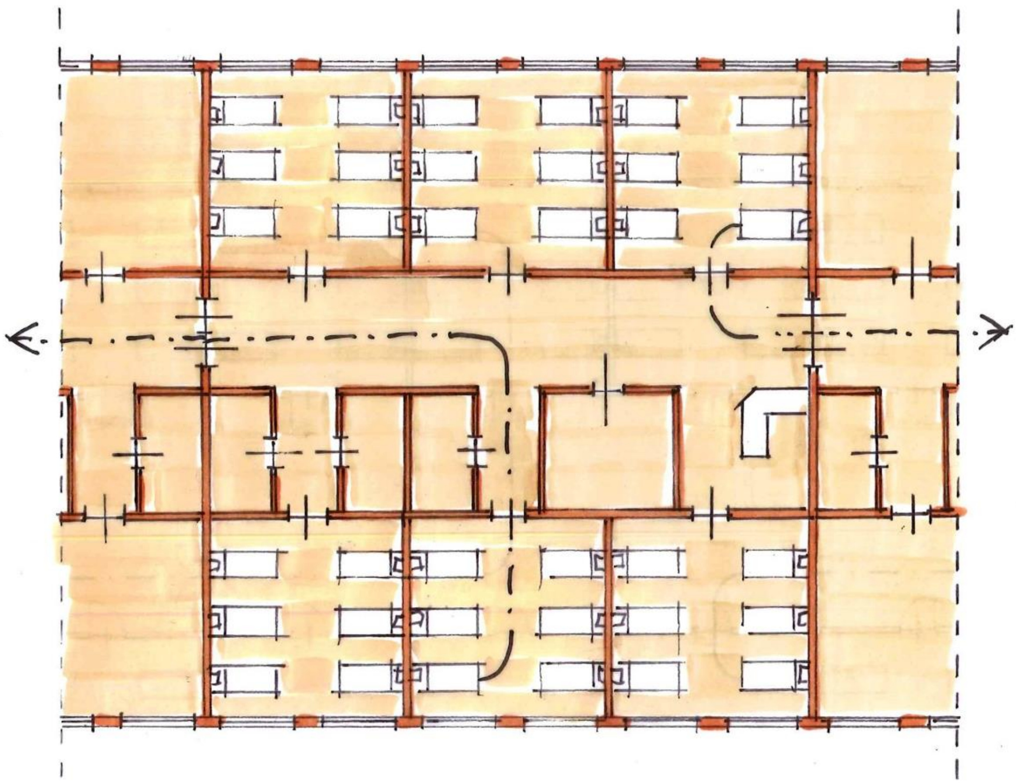


Figure 1 Layout of standard hospital ward based maximum permissible of Dutch Building Decree.

Type of ward	Number of patients	Uncoupling time per patient [s]	Average RSET entire ward [mm:ss]	RSET including standard deviation [mm:ss]
Basic patient	36	5,5	13:23,9	15:52,7
Standard patient	36	30,7	17:16,4	19:55,0

Table 1 Overview of RSET with different types of patients.

Basic layout

The layout is based on a standard layout as seems to be occurring in older hospitals. The ward is a combination between different sizes of patient rooms. The fire compartment is 500 m2. A comparison is made when the ward doesn't have self-closing doors, and have to be closed by staff. The probability of casualties displayed in graph 9.3 is for the ward with self-closing doors.

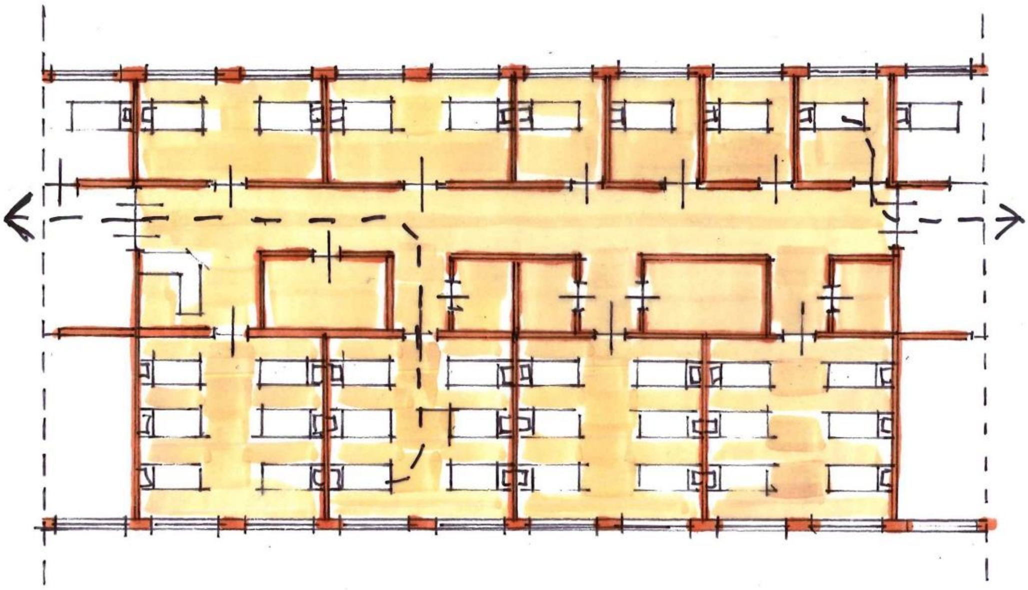
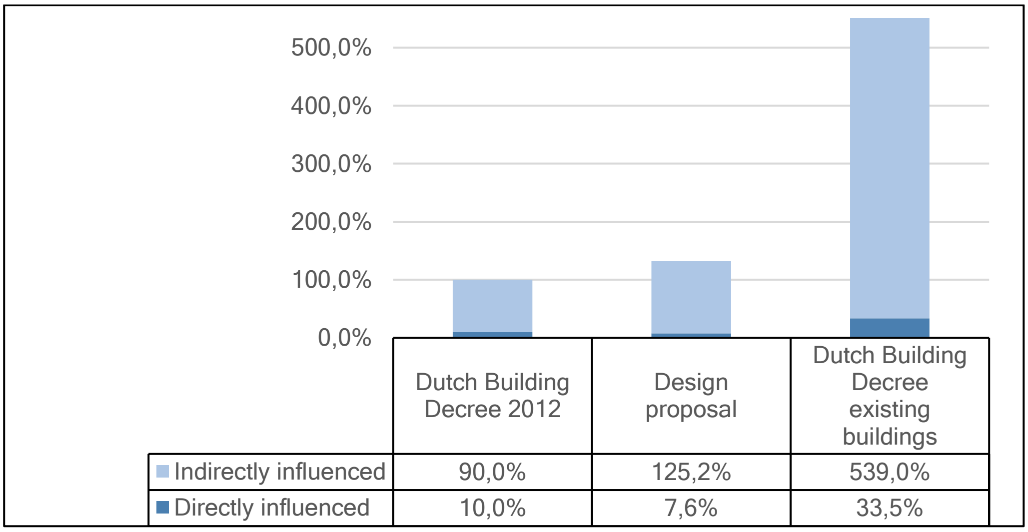


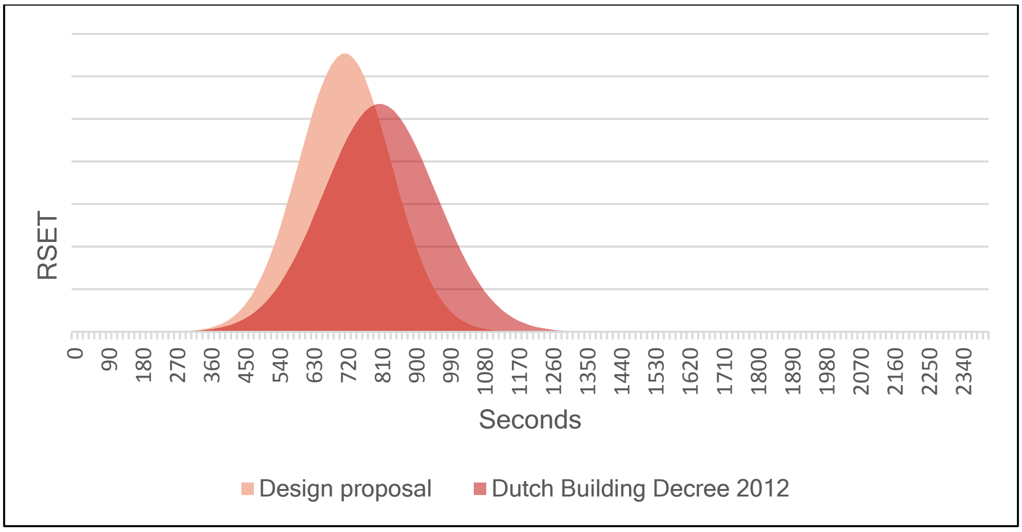
Figure 2 Layout of standard hospital ward based on common hospital wards.

Type of ward	Number of patients	Uncoupling time per patient [s]	Average RSET entire ward [mm:ss]	RSET including standard deviation [mm:ss]
Basic patient	32	5,5	11:52,1	13:53,9
Standard patient	32	30,7	15:28,9	17:41,8

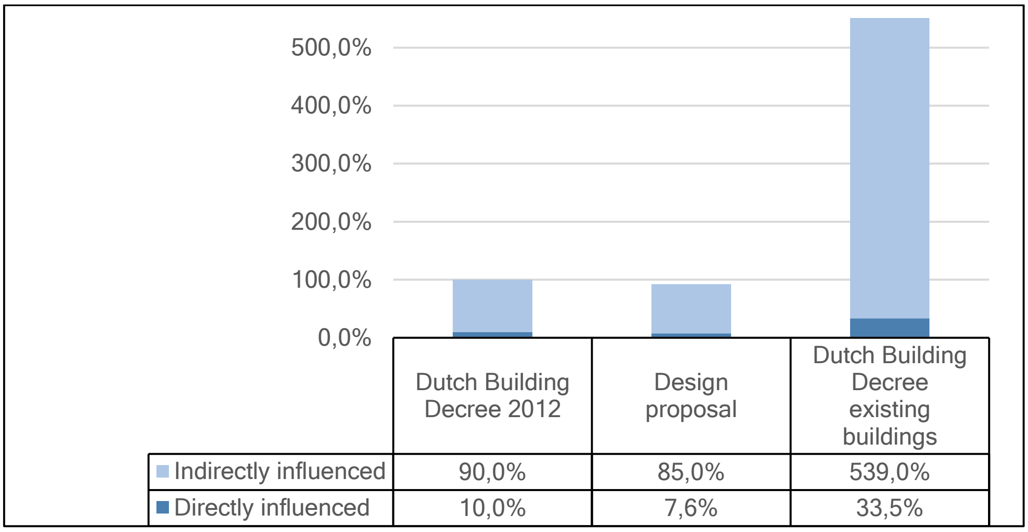
Table 2 Overview of RSET with different types of patients.



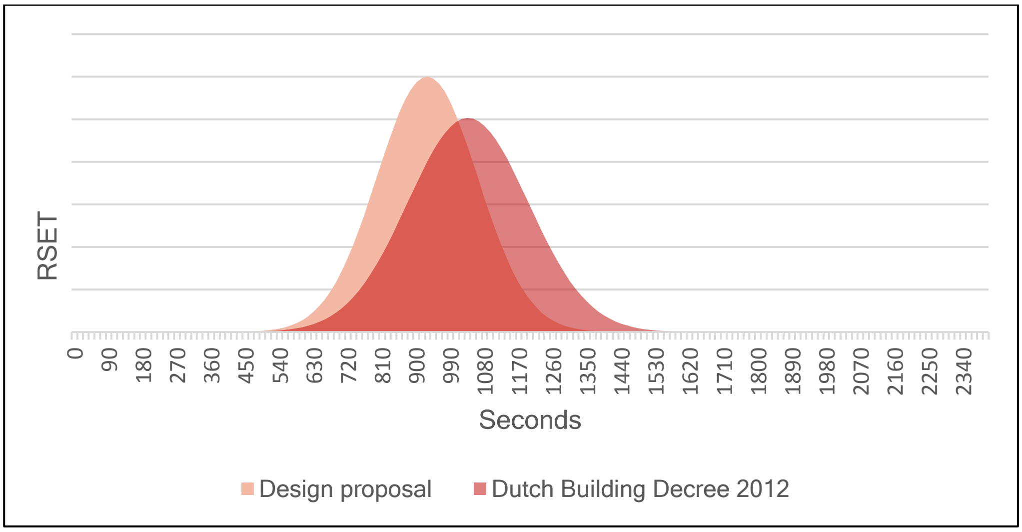
Graph 1 Probability of casualties of common ward compared with Dutch Building Decree hospital ward.



Graph 2 RSET of ward with basic patient



Graph 3 Probability of casualties of common ward with self-closing doors compared with Dutch Building Decree hospital ward.



Graph 4 RSET of ward with standard patient.

Single patient rooms

The layout is based on a ward with only single patient rooms and a wider corridor, following the new architectural design trends. The fire compartment is 487 m2.

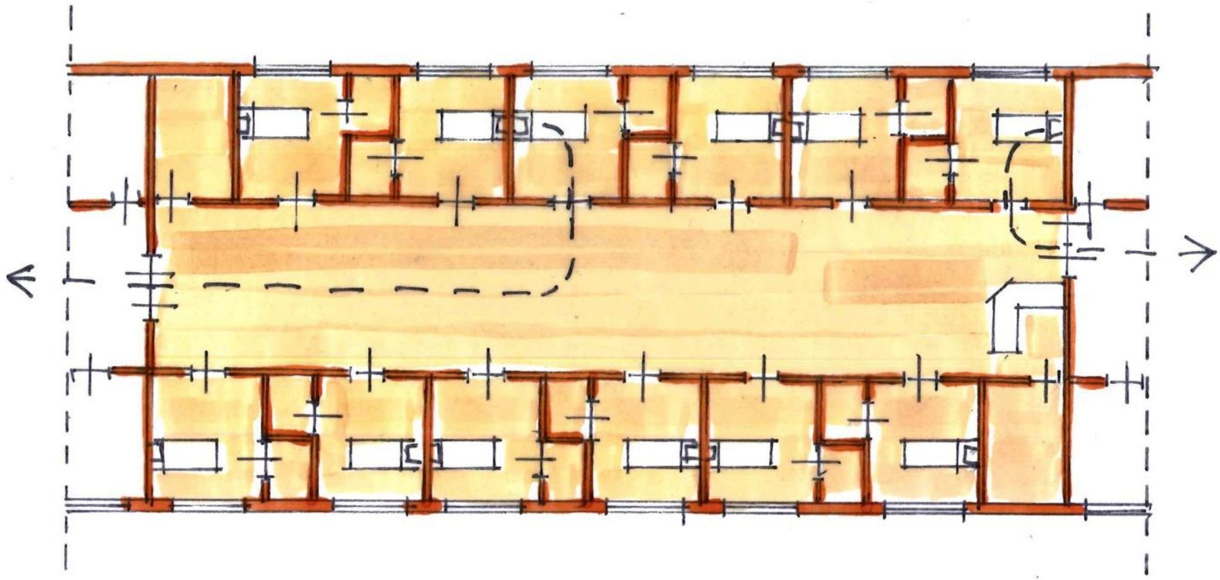
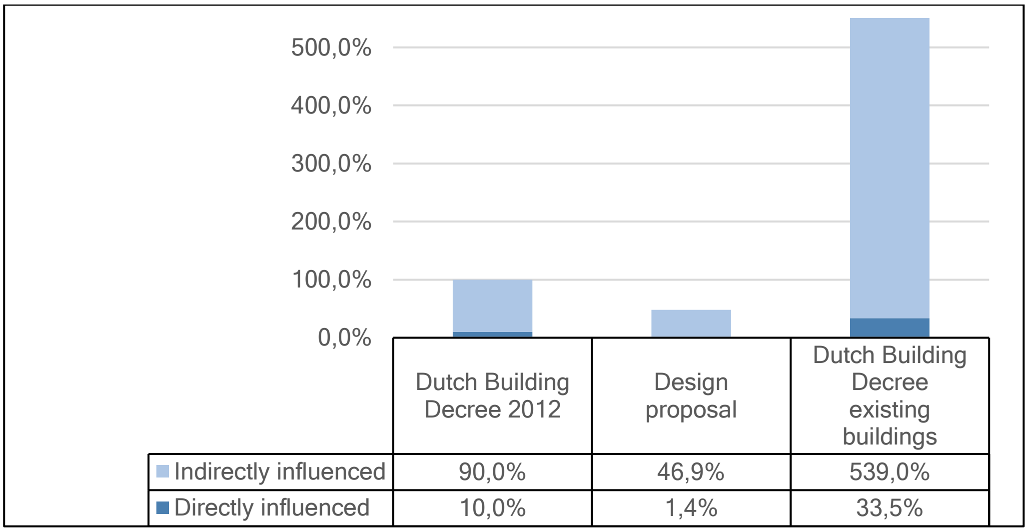


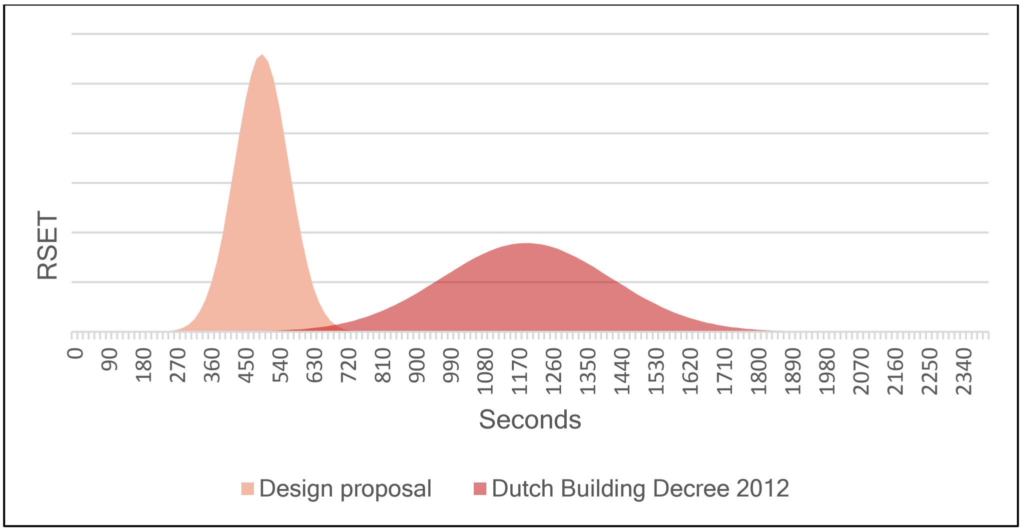
Figure 3 Layout of hospital ward based on new architectural design trends.

Type of ward	Number of patients	Uncoupling time per patient [s]	Average RSET entire ward [mm:ss]	RSET including standard deviation [mm:ss]
Basic patient	12	5,5	08:13,2	09:24,5
Standard patient	12	30,7	10:44,4	12:08,2
Heart monitoring	12	33,5	11:01,2	13:04,1

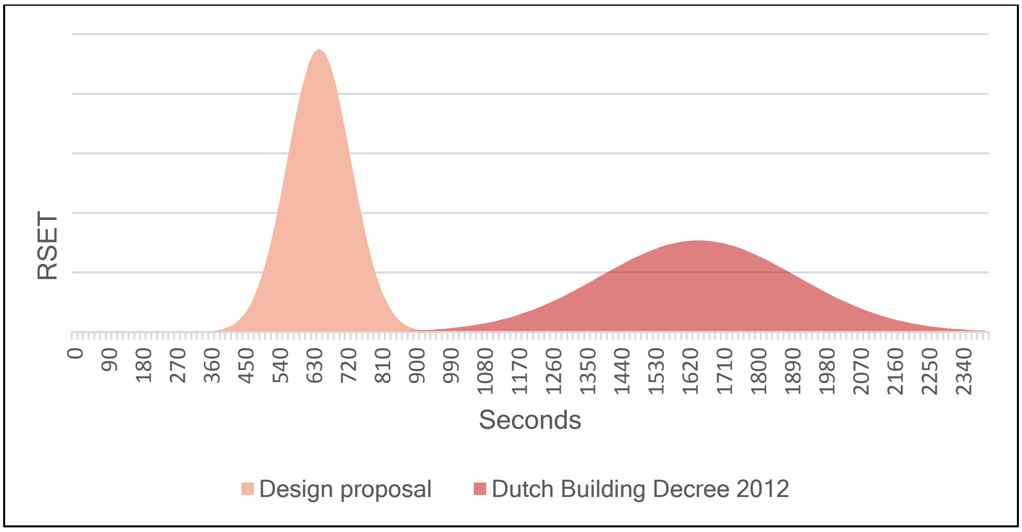
Table 3 Overview of RSET with different types of patients.



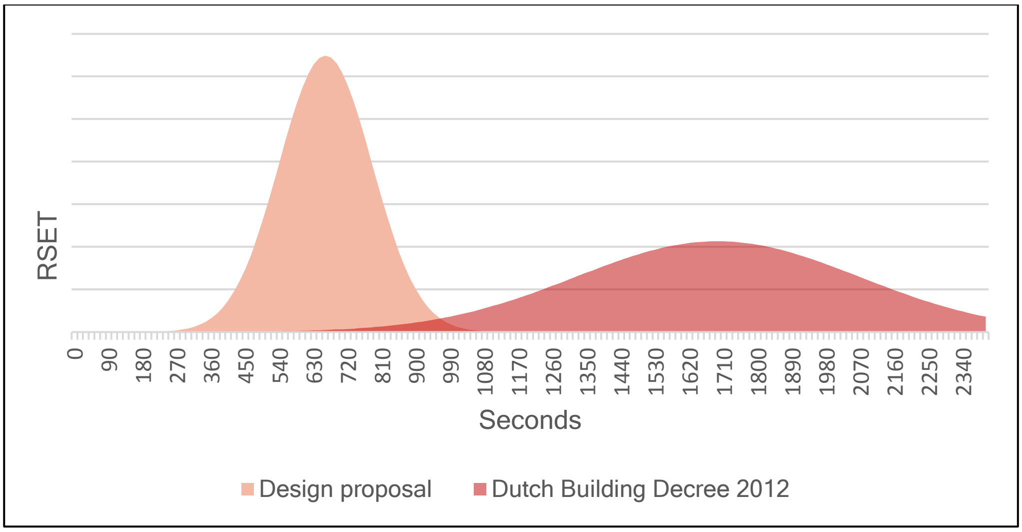
Graph 5 Probability of casualties of design proposal compared with Dutch Building Decree hospital ward.



Graph 6 RSET of proposed layout compared with Dutch Building Decree.



Graph 7 RSET of proposed with uncoupling times of standard patient.



Graph 8 RSET of ward with uncoupling times of heart monitoring patient.

Ward with reduced risks

The layout is based on a ward with a small corridor, where the risk on fire is less because of material choices. To reduce the risk more, the auxiliary rooms and the nurse station are placed in a different compartment. The fire compartment with the patient rooms is 410 m2. Hence the RSET is almost equal to the RSET of the compared DBD ward, the relative risk on casualties is significantly lower. Stated can be that the design is safer than required in regulations.

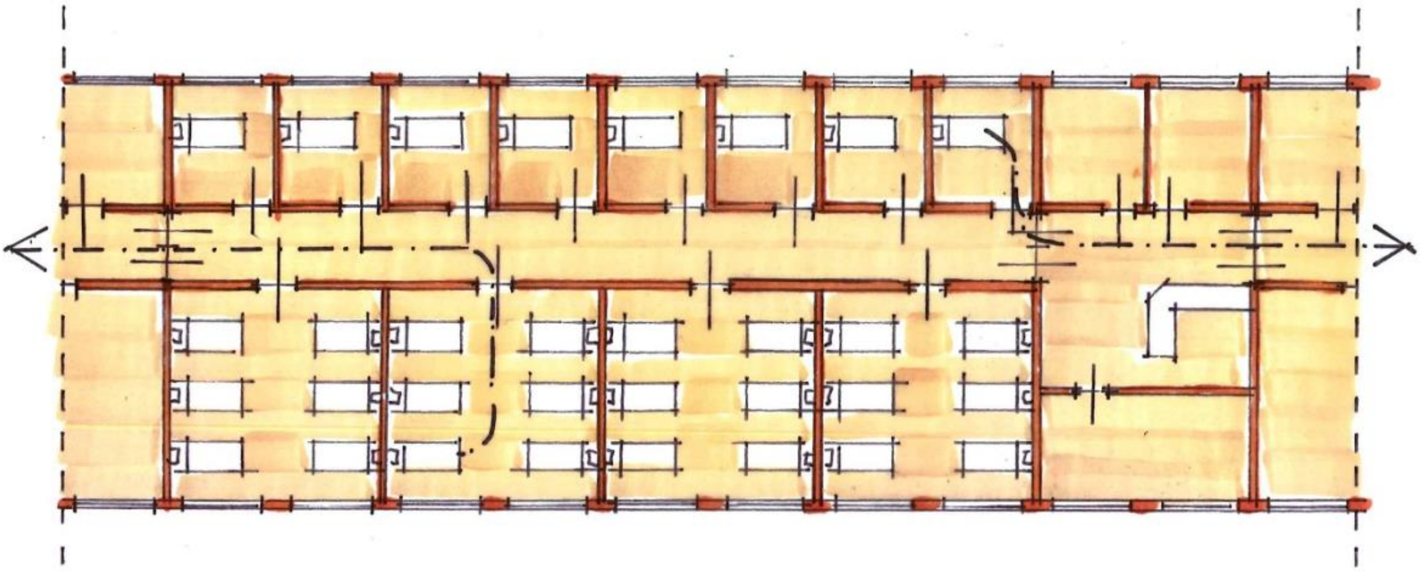
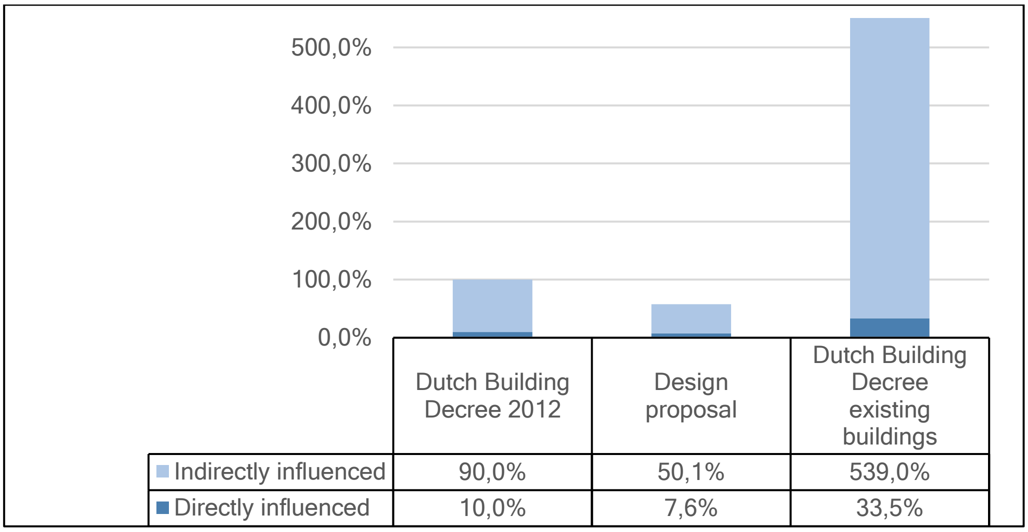


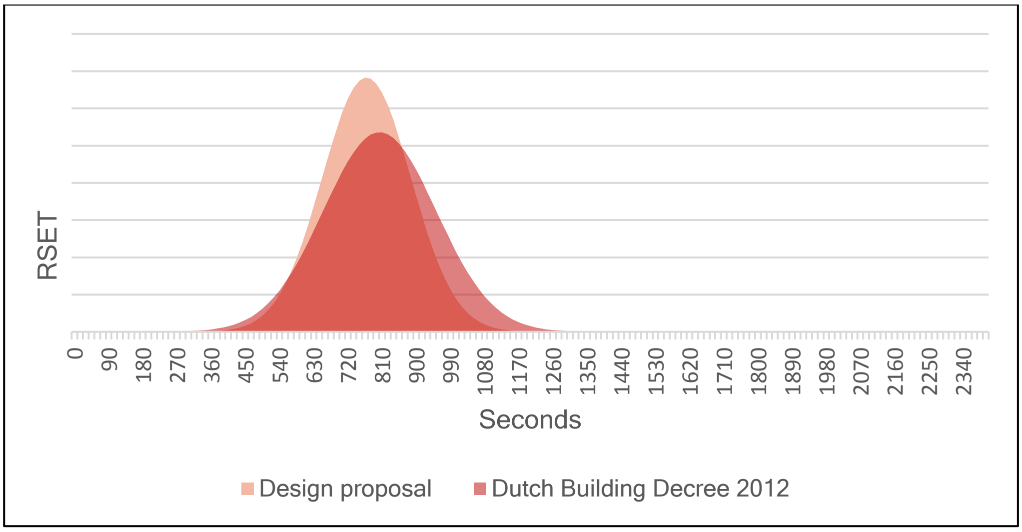
Figure 4 Layout of hospital ward based on new architectural design trends.

Type of ward	Number of patients	Uncoupling time per patient [s]	Average RSET entire ward [mm:ss]	RSET including standard deviation [mm:ss]
Basic patient	32	5,5	12:49,0	14:45,8
Standard patient	32	30,7	16:17,0	18:35,0
Heart monitoring	32	33,5	16:44,9	20:08,6

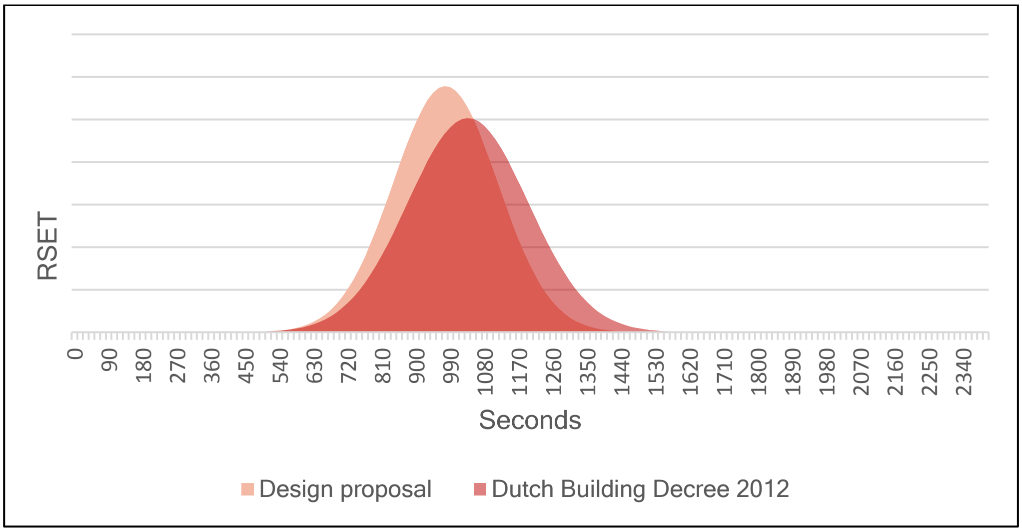
Table 4 Overview of RSET with different types of patients.



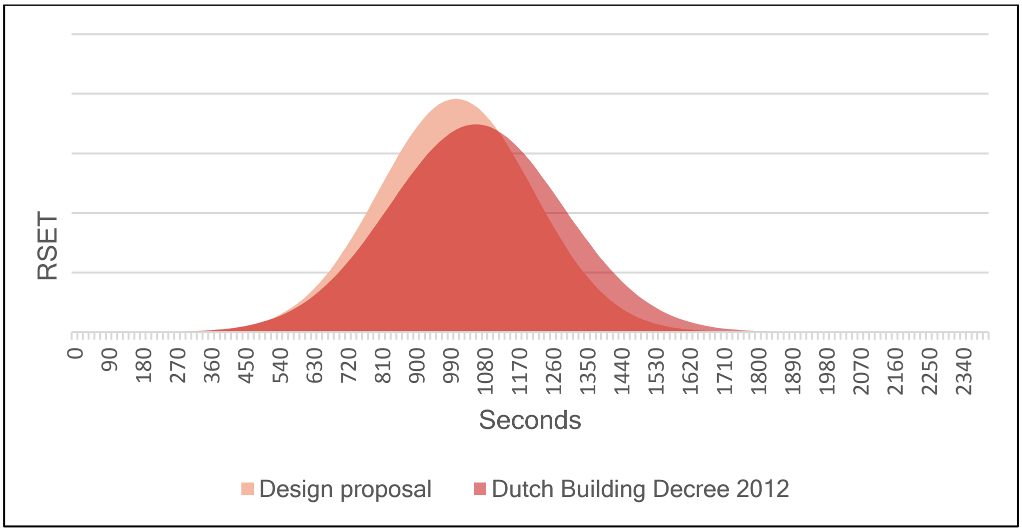
Graph 9 Probability of casualties of design proposal compared with Dutch Building Decree hospital ward.



Graph 10 RSET of ward with basic patient.



Graph 11 RSET of ward with standard patient.



Graph 12 RSET of ward with heart monitoring patient.

Hospital ward with stairs

The layout is based on a ward with only single patient rooms and a wider corridor, following the new architectural design trends. The fire compartment is 487 m2. The RSET is calculated for a scenario when half the patients must be evacuated down the stairs, using a movement assist device.

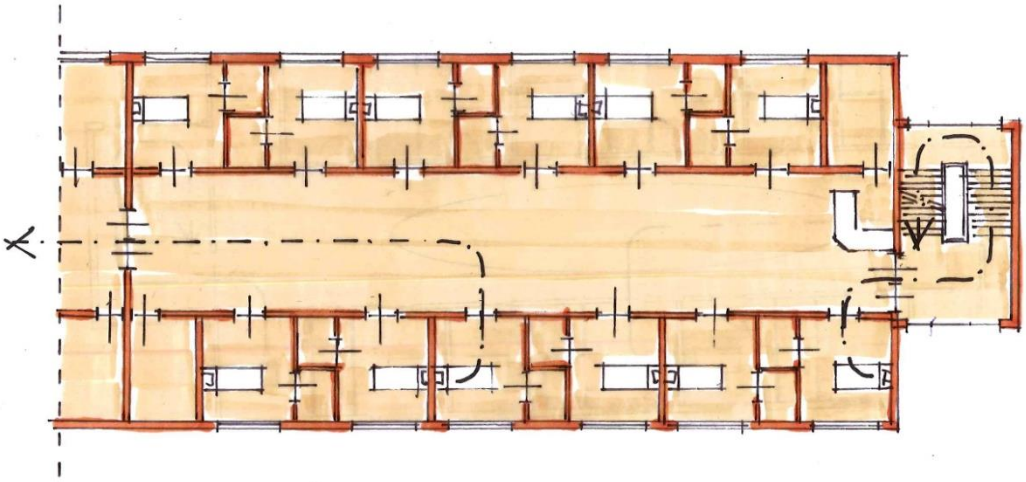
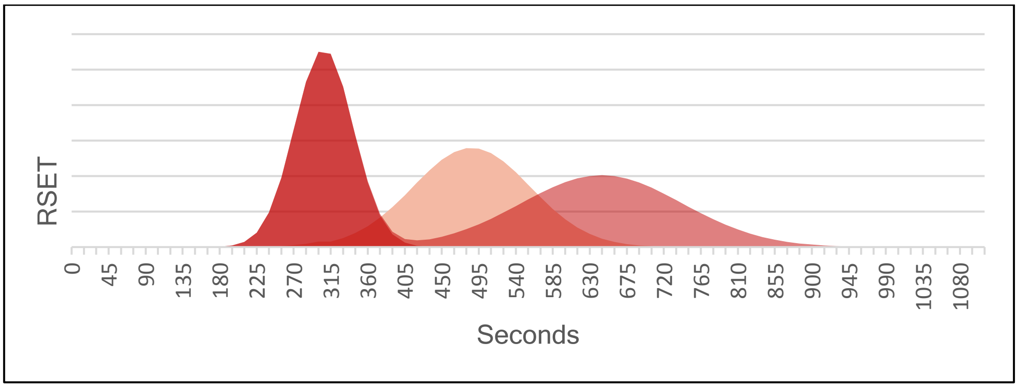


Figure 5 Layout of hospital ward with staircase as evacuation route.

Type of ward	Number of patients	Uncoupling time per patient [s]	Average RSET entire ward [mm:ss]	RSET including standard deviation [mm:ss]
Basic patient	12	5,5	08:13,2	09:24,5
Basic patient (6 evacuated down stairs)	12	5,5	19:28,1	25:27,2

Table 5 Overview of RSET when patients must be evacuated down stairs by movement assist device.



Graph 13 RSET of hospital ward, when 6 out of 12 patients must be evacuated via stairs, compared with a regular evacuation.

Hence the risk for a fire occurring in the ward is the same, a fire compartment with stairs at the end will need extra measures to make sure the risk as approached will be the same as other wards without stairs.

Specific wards

Dutch Building Decree

The layout is based on the maximum permissible values of the current Dutch Building Decree. The fire compartment is 500 m2 without any sub fire compartments, when permanent surveillance is present.

The percentages calculated for this layout will be taken as basic value to compare with other layouts of specific hospital wards.

The staff patient ratio for specific wards is in most hospitals higher, then for the regular wards. Therefore, the RSET calculations are made with 4 staff members present on the ward, and 2 extra staff members with an arrival time of 2 minutes.

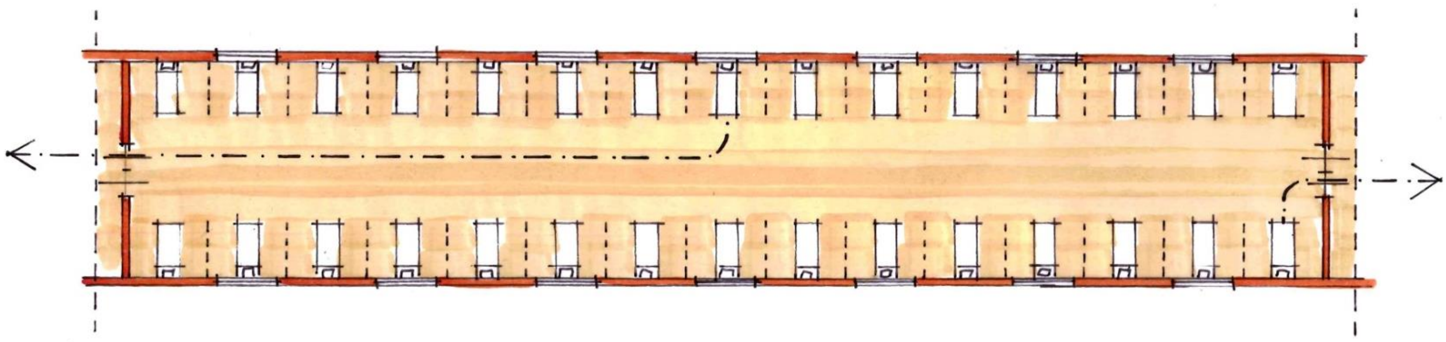


Figure 6 Layout of standard hospital ward based maximum permissible of Dutch Building Decree.

Type of ward	Number of patients	Uncoupling time per patient [s]	Average RSET entire ward [mm:ss]	RSET including standard deviation [mm:ss]
Basic patient	30	5,5	09:44,8	11:39,6
Dialysis	30	15,3	11:44,9	13:47,3
Recovery	30	28,5	13:56,9	16:57,6
Intensive Care	30	89,2	24:03,9	28:33,5

Table 6 Overview of RSET with different types of patients.

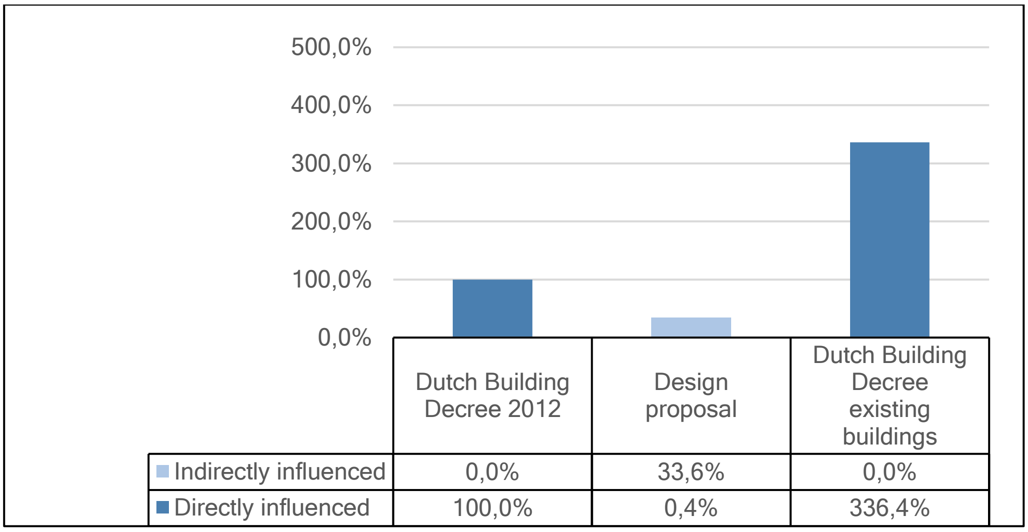
Basic layout

The layout is based on a standard layout as seems to be occurring in hospitals. The ward is a combination between open space with patients, and single patient rooms. The fire compartment is 500 m2. The RSET graphs 9.20 till 9.23 show the differences in RSET if the gathered data of evacuation times of specific patients is applied. If the risks have the be the same for every ward, extra measures are necessary to make wards with a longer RSET safer.

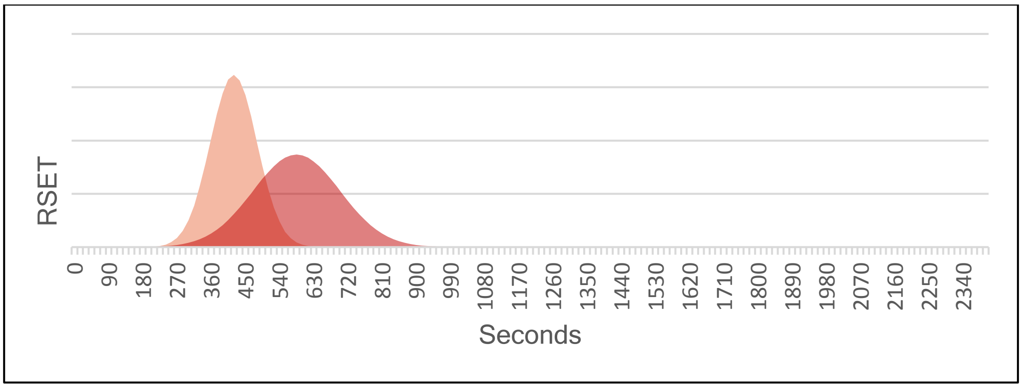
Figure 7 Layout of specific hospital wards as in common hospitals.

Type of ward	Number of patients	Uncoupling time per patient [s]	Average RSET entire ward [mm:ss]	RSET including standard deviation [mm:ss]
Basic patient	12	5,5	06:59,2	08:01,0
Dialysis	12	15,3	07:38,4	08:42,5
Recovery	12	28,5	08:31,3	09:54,5
Intensive Care	12	89,2	12:34,1	14:29,5

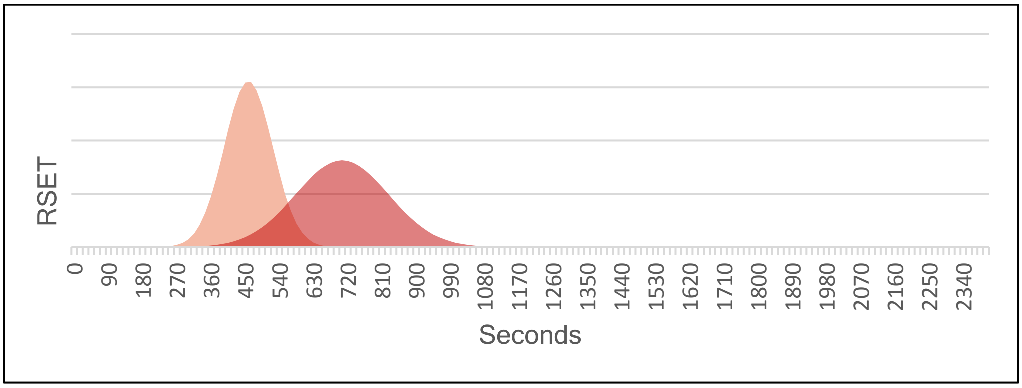
Table 7 Overview of RSET with different types of patients.



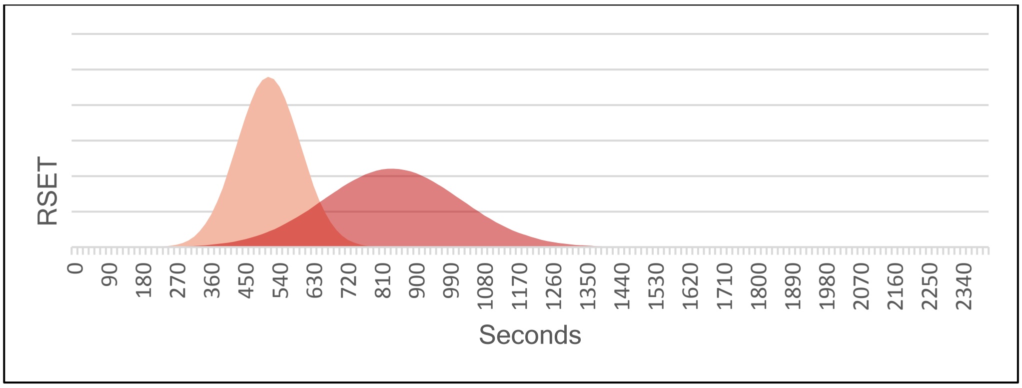
Graph 14 Probability of casualties of design proposal compared with Dutch Building Decree hospital ward.



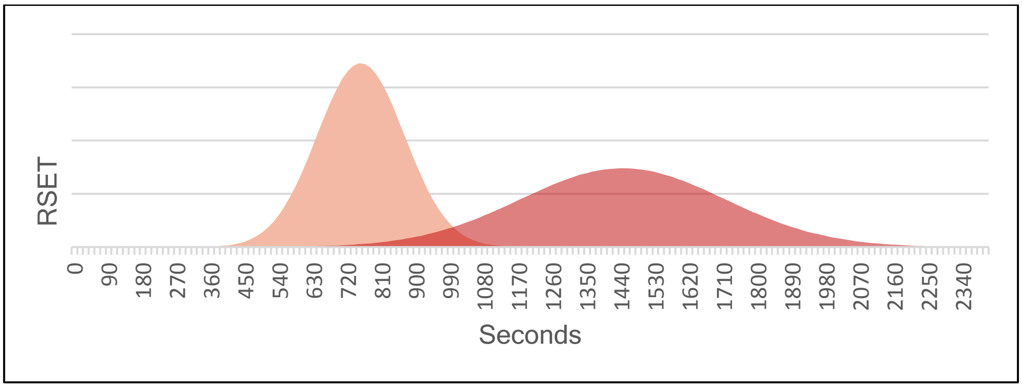
Graph 15 RSET of ward with basic patients.



Graph 16 RSET of ward with Dialysis patients.



Graph 17 RSET of ward with Recovery patients.



Graph 18 RSET of ward with Intensive Care patients.

Single patient rooms

The layout is based on a specialised ward with only single patient rooms. The fire compartment is 500 m2, and contains 8 patient rooms. With shifting the ward to single patient rooms the relative risk on casualties is significantly lower.

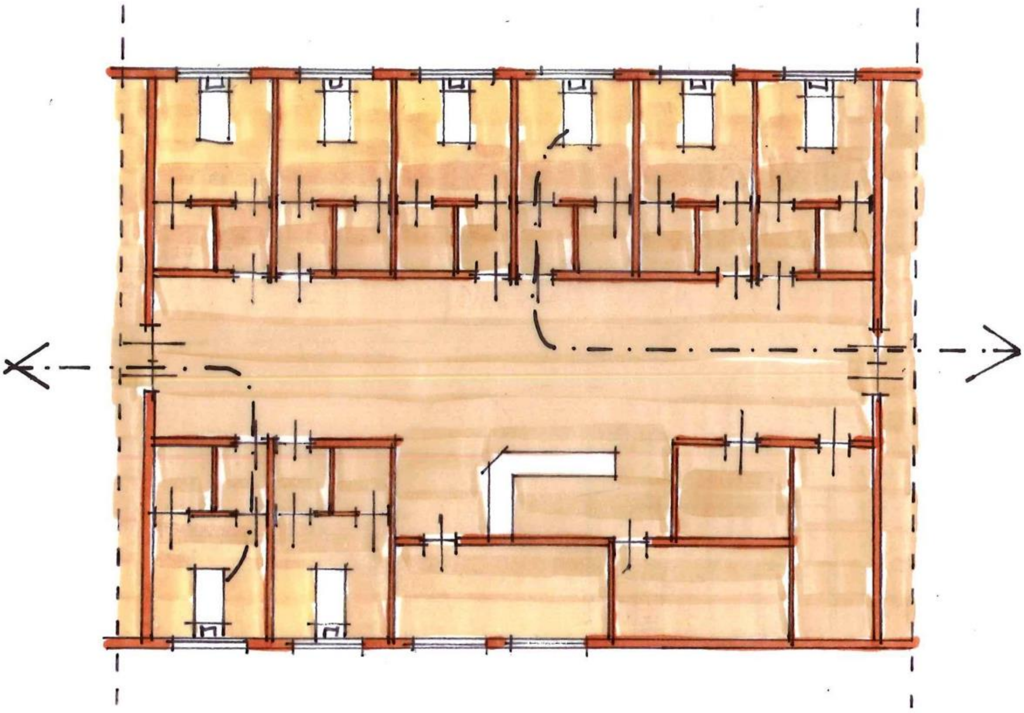
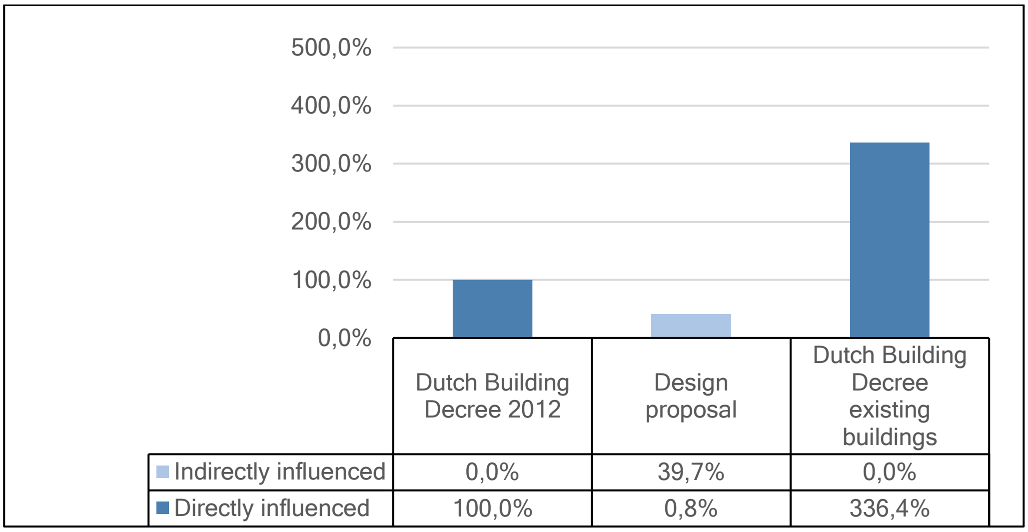


Figure 8 Layout of specific hospital ward based on new architectural design trends.

Type of ward	Number of patients	Uncoupling time per patient [s]	Average RSET entire ward [mm:ss]	RSET including standard deviation [mm:ss]
Basic patient	8	5,5	04:50,9	05:22,7
Dialysis	8	15,3	05:15,4	05:49,7
Recovery	8	28,5	05:48,5	06:41,1
Intensive Care	8	89,2	08:43,3	10:03,1

Table 8 Overview of RSET with different types of patients.



Graph 19 Probability of casualties of design proposal compared with Dutch Building Decree hospital ward.