Legislative and technical requirements for applying gravity-feed systems for operation of sprinkler systems in high-rise buildings

Graduation thesis

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Legislative and technical requirements for applying gravity-feed systems for operation of sprinkler systems in high-rise buildings

Final report

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I, Max Verbruggen, hereby declare that this thesis entitled “Legislative and technical requirements for applying gravity-feed systems for operation of sprinkler systems in high-rise buildings” is my own work.

Preface

This thesis was written as part of the graduation internship done during the bachelor Aviation Engineering at the Amsterdam University of Applied Sciences. It focusses on creating an overview of the legislative and technical requirements for applying a gravity-feed sprinkler system in high-rise building and the creation of design guidelines for such systems according three normative frameworks: NEN, NFPA, and FM Global.

I would like to express my thanks to Daan Jansen and René Jansen for providing me the opportunity to finish my bachelor's degree at Royal HaskoningDHV. Their excellent guidance during this thesis has allowed to achieve the results that I have been able to produce. Their expansive knowledge on the subject of fire safety systems has helped me in many sparring sessions and gaining a clearer overview of the problem at hand. Furthermore, I would like to thank everyone within the Fire Safety & Security team for their help and knowledge. The warm atmosphere and approachability within the team allows me to flourish in my position and has been a boon to my professional growth. I would also like to thank Marc Bijvoet for lending his ear and his insight as a constructor with regards to possible structural issues of large volume water tanks at altitude within buildings. Lastly, I would like to extend my gratitude toward my coaching lecturers Margriet Klompstra and Maria Papanikou for their support over the course of this thesis. The structured meetings helped me to keep an overview of what was necessary and to keep a level head. Furthermore, their experience and knowledge on report writing has been especially helpful, for report writing is still an area of improvement. I look forward to joining the Fire Safety & Security full-time and to work alongside this great team within Royal HaskoningDHV.

Management Summary

Currently, in high-rise buildings a traditional pumped system is used to operate the sprinkler system. However, due to the height of the building this means large multi-stage pumps must be placed compensate for the static pressure losses. A solution to this is utilizing a gravity-feed system, where the sprinkler system is pressurized by water tanks placed at altitude above the sprinklers. Gravity-feed systems supply the sprinkler system with pressure by utilizing gravity, without the need for fire pumps. Only the top floors, where there is not yet enough height between the water tank and sprinklers, need to be protected using a much smaller pump. Some normative frameworks have already included some legislation surrounding the use of gravity-feed systems. However, guidelines to design gravity-feed systems do not yet exist. The goal of this research is to provide an overview of the considerations of designing gravity-feed sprinkler systems and to create a general design guideline for NEN, NFPA, and FM Global. As such, the main research question is:

"What are the legislative and technical requirements for applying gravity-feed systems for operation of sprinkler systems in high-rise buildings according to NEN, NFPA, and FM Global so that design guidelines can be written?"

The first step in designing any sprinkler system is to understand the design criteria set by the normative framework that is chosen for the system. Therefore, for each normative framework an overview was created of all relevant design criteria for sprinkler systems. Design criteria are based of the hazard being protected. These hazards depend on the occupancy of a room and are divided over hazard classifications. These hazard classifications dictate the requirements which the sprinkler system must be able to fulfil. Water tanks that supply the sprinkler system are also subject to requirements imposed by the normative frameworks. The water tanks must be sized to able to supply the sprinkler system over the entirety of the sprinkler duration. Furthermore, the water tanks must be able to be refilled within 8 hours after activation. It must also be considered water tanks placed at height exert more force than a floor is typically designed for. The structure must therefore be reinforced around the water tank with the use of divider walls between support columns to create a strong box for the water tank.

With the use of the design criteria, six test scenarios were made to determine with the use of hydraulic analysis, the recommended system design per hazard classification per normative framework. These six scenarios include: a residential area, offices, an underground parking garage, a grocery store, a bakery, and a cinema theatre. The hazard classifications considered for this research cover only the low and medium hazard classifications, as the heavy hazard classifications are not expected to be present within high-rise buildings. For each test scenario a detailed design was made to calculate the minimum height difference between the water tank and sprinklers and pipe diameters for the system. For these calculations a baseline reduction of 25% was used in the maximum area per sprinkler. This is to adjust for any obstructions or complex geometry that often challenge real designs.

With the use of hydraulic analysis it was determined that gravity-feed systems can realistically protect high-rise buildings. The minimum height difference between the water tank and sprinklers is between 15-33 meters depending on the hazard classification. The maximum height difference is limited to roughly 120 meters as sprinkler system components are rated a pressure of 12 bar and the static pressure increases with 0,98 bar per ten meters. It was also found that the system consumption per minute increases greatly with greater height differences. An increase in consumption requires the water tank to enlarged to meet the demand. This can be alleviated by constricting the pipe diameters after a certain height below the water tank depending on the hazard classification. This increases the friction losses and thus reduces system consumption. Furthermore, it was determined that NFPA is the favourable framework for designing gravity-feed systems in high-rise buildings. This is because NEN enforces heavier hazard classifications if the height

difference between the lowest and highest sprinkler exceeds 45 meters. FM Global demands higher design criteria which result in a larger system consumption and thus larger water tanks.

From these results, design guidelines were created for the three normative frameworks. These guidelines serve only as a starting point for designing gravity-feed systems. Designs made with these guidelines still must be substantiated with the use of hydraulic analysis. It is recommended to use NFPA and to place at least two water tanks. The first is placed at the optimal height to protect the heavier hazard classifications typically found the lowest floors so that it does not need to enlarged to account for increased system consumption. The top floors are typically occupied by residences or offices. These are light hazard classifications and thus the effects of increased system consumption over height have a smaller effect on tank size. The second tank should be placed on the top floor. The top four to five floors cannot yet be protected by the water tank using the gravity-feed system as the height difference is not large enough. Therefore, these floors must still be protected using a fire pump. However, this pump can be much smaller as it does not need to overcome nearly any static pressure loss.

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Acronyms

AHJ	Authority Having Jurisdiction
CEN	European Committee for Standardization
DN	Diameter Nominal
EH	Extra Hazard
EN	European Norms
FM Global	Factory Mutual Global
HC	Hazard Category
ISO	International Organisation for Standardization
LH	Light Hazard
NEN	Netherlands Standardization Institute
NFPA	National Fire Protection Association
OH	Ordinary Hazard
PLG	Peer Learning Group
RHDHV	Royal HaskoningDHV

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Glossary

Table 1: Glossary of terms used within the research

Term	Explanation
Design criteria	A summary of design requirements specific to an occupancy, building, or scenario for which a sprinkler system is designed. It forms the basis upon which a detailed design can be made.
Design requirements	A part of the legislative requirements specifically related to the design of sprinkler systems.
Dry pipe system	A sprinkler system which uses air or nitrogen to pressurize the system. After activation the air or nitrogen then escapes which allows water to enter the system and operate the sprinklers. (NFPA, 2021b)
Gravity feed system	A sprinkler system which employs gravity to provide the requisite pressure to operate the system. This is achieved by placing a water tank at altitude above the sprinklers.
Hazard classification	A collective term for the classification of the level of fire hazard present within an occupancy. NEN refers to this as hazard classes, NFPA as occupancy hazards, and FM Global as hazard categories. Hazard classifications are used to determine the level of protection a sprinkler system must be able to provide.
Hydraulic analysis	A method used to validate the design of a sprinkler system. This includes the calculation of the flow rate, supplied water pressure, volume, losses, and spray density. Furthermore, in case of dry pipe systems the water delivery time is also calculated (Vishnoi, 2017).
Legislative requirements	A term to describe any and all requirements set by the normative frameworks. These requirements govern the requirements which a sprinkler system must comply with. Under these requirements fall the design requirements as well as water supply requirements and other requirements which are not within scope of this research.
Normative framework	A document or set of documents written by an organisation that provide the recommended design practices for sprinkler systems. These are not inherently legally binding but are often enforced by authorities as legislation for certification of sprinkler systems.
Occupancy	The manner in which a space within a structure is utilized. This can be divided into occupancies where storage is present and occupancies without storage. Based on the types of goods and/or processes present within an occupancy a hazard classification can be determined.
Sprinkler system	A system, commonly activated by heat from a fire and discharges water over the fire area. Which consists of an integrated network of piping designed in accordance with fire protection engineering standards (NFPA 13, 2021b).
Technical requirements	A summary of specifications for a sprinkler system design based on results of the hydraulic analysis. This includes the pipe diameters chosen for the different types of pipes within the sprinkler system.
Water delivery time	The time interval between the opening of a sprinkler head within a sprinkler system and the point in time when the pressure at this sprinkler head reaches or surpasses the design pressure for the sprinkler system (FM Global, 2024).
Water supply requirements	A part of the legislative requirements specifically related to the design of water supply system.
Water supply systems	The part of the sprinkler system which supplies water to the sprinklers. This includes the water-storage tanks, fire pumps, pipes, and valves present within the system.
Wet system	A sprinkler system which employs water to pressurize the system. After activation water is immediately discharged from the sprinklers (NFPA, 2021b).

1 Introduction

Firstly, the background of the problem is described (Section 1.1). From this, the problem statement can be derived (Section 1.2). Afterwards, the objectives of this research and how this research contributes to the personal objectives of RHDHV is described (Section 1.3). The relevance and significance of this research is then discussed (Section 1.4). Using the problem statement, it is possible to formulate the main and sub research question (Sections 1.5 & 1.6). Lastly, the scope of the research is defined (Section 1.7) and the report structure is described (Section 1.8).

1.1 Background of the problem

Royal HaskoningDHV, hereafter referred to as RHDHV, is an international engineering and project management consultancy firm. The company specialises in project specific solutions based on collaboration between firm and client. This spans across different disciplines in the fields of infrastructure, water, maritime, aviation, industry, buildings, and energy. The core values of RHDHV are actively contributing to the furtherment of innovation and sustainability for the improvement of society. Within the field buildings is the department of Fire Safety and Security. This department specialises in providing complete consultancy solutions for designing and maintaining fire safety systems within industrial and civil buildings. Furthermore, members of this department are also active within legislative advisory bodies and help shape current and future rules and regulations.

This research originates from the desire to design sprinkler systems more efficiently for use within high-rise buildings. Currently, fire pumps are placed in the basement or on the ground floor of buildings. In high-rise buildings this means the size of these pumps must be increased to account for the static pressure loss due to the difference in height from pump to sprinkler zone. An alternative to the conventional fire pumps is to apply gravity-feed systems. Gravity-feed systems rely on gravitational forces to deliver the requisite pressure and flow for operation of sprinklers within a building. However, this is still rarely applied since no guidelines for designing such systems exist. Though some normative frameworks have already included regulation for gravity-feed systems. Because of this, this research aims to provide a comprehensive overview of the benefits and constraints for applying gravity-feed systems specifically for the application in high-rise buildings. Furthermore, this research will provide guidelines for designing these systems based on three major normative frameworks; Netherlands Standardization Institute (NEN), National Fire Protection Association (NFPA), and Factory Mutual Global (FM Global). Guidelines will be substantiated using hydraulic calculations with SprinkCALC software from Johnson Controls.

1.2 Problem statement

Currently, sprinkler systems are pressurized and fed through conventional fire pumps. These can be electric or diesel pumps. Pumps are typically placed in the basement or on the ground floor and must thus, in high-rise buildings, compensate for large static pressure losses due to the difference in altitude between the pump and sprinkler zones. This means that larger, more powerful pumps must be placed to accommodate at greater expense of installation and maintenance for the building owner. A possible alternative to this is applying gravity-feed systems. These rely on gravitational forces to provide the pressure and flow necessary to operate the sprinkler system. This would reduce the number of fire pumps necessary to operate the sprinkler system. This comes at a clear benefit of cost of installing and maintaining a sprinkler system as there are fewer and smaller pumps necessary. This would reduce the number of moving parts that need more intensive maintenance and inspection. Furthermore, this also reduces other costs that come with conventional fire pump systems. Both types of fire pumps require certain measures to be taken to allow for safe and reliable operation of the sprinkler system. For diesel pumps fuel tanks must be placed and exhaust gasses must be properly ducted out to a safe location. The pump room and fuel room, if placed separately, must also be protected by the sprinkler system according to a relatively strict hazard classification. Furthermore, measures must also be taken against the sound the pump produces to avoid disturbing the environment. For electric pumps measures must be taken to ensure that a sufficient power supply is at all times available to operate the pump. This includes an emergency power generator. Fewer or no fire pumps thus reduce the cost of organisational requirements. This will make it easier for fire consultants and contractors to design sprinkler systems in high-rise buildings. Additionally, fewer, smaller diesel pumps produce less carbon emissions and are thus more sustainable.

Gravity-fed have already been applied in few buildings, but no guidelines are as of yet available for designing such systems. Placing large volume water storage tanks for sprinkler systems may also pose some structural problems. This makes it desirable for research to be done into the technical and legislative requirements for applying gravity-feed systems. If properly substantiated, guidelines can be set up that aid fire safety engineers in designing these systems in the future. This research can then also be used to substantiate to inspection and certification institutes, which provide approval of sprinkler system conformity to rules and regulation.

1.3 Research objective

This research consists of both qualitative and quantitative research. Firstly, research is conducted into the legislative requirements for sprinkler systems according to three major normative frameworks; NEN, NFPA, and FM Global. This includes the different hazard classifications per normative framework as well as requirements for water storage tanks, refill requirements, and possible miscellaneous requirements of interest for this research. Furthermore, research is done into possible constraints for placing water storage tanks at altitude. From this, a comprehensive overview of legislative and organisational requirements is made.

Several test scenarios are created based on building occupations that can reasonably be expected from high-rise buildings. These scenarios are used to calculate the pipe diameters and height difference between the water tank and sprinklers necessary. Every scenario is then worked out to detail the placement and size of sprinklers, pipes, and sprinkler zones as per the legislation. Each scenario is substantiated using hydraulic calculations.

From these calculations guidelines are then created that detail per normative framework matters such as minimum height difference between the water tank and sprinkler and pipe diameter based on scenario. These guidelines can then be used in the future as a starting point to design gravity-feed systems quickly and efficiently in other high-rise buildings.

This research closely aligns with the core values of RHDHV such as innovation into possible innovation and advancement of sustainable solutions. RHDHV believes in a constant search for improvement and aims to continuously challenge itself to contribute to solving complex engineering and social issues. This research contributes to this as it aims to change the status quo regarding the design of sprinkler systems in high-rise buildings. RHDHV is also very active in the field of sustainability and sustainable solutions. This research also actively contributes to decreasing the carbon footprint of high-rise buildings by the reduction or absence of diesel pumps necessary for sprinkler systems as less or no exhaust gasses will be produced by its operation.

1.4 Research significance

The goal of this research is to gain a comprehensive overview of the technical and legislative requirements for applying gravity-feed systems in high-rise buildings. From this overview, guidelines are also created that provide guidance on designing and implementing these systems in the future. This will possibly lead to reduced construction and maintenance costs for sprinkler systems. Furthermore, the application of these systems also contributes to reducing the carbon footprint of high-rise buildings due to the possible reduction or absence of diesel pumps and its exhaust gasses.

1.5 Main research question

From the problem statement a main research question can be derived. This is the main question the research shall strive to answer. The main research question is:

“What are the legislative and technical requirements for applying gravity-feed systems for operation of sprinkler systems in high-rise buildings according to NEN, NFPA, and FM Global so that design guidelines can be written?”

1.6 Research sub-questions

To support the main research question, several sub-research questions are set up. These questions help answer the main research question and answer more specific questions that the main research question raises. The research sub-questions are:

1. **What are the legislative requirements for designing sprinkler systems?**

Research is done into the three normative frameworks that are within the scope of this research. The goal is to gain an overview of the different hazard classifications per framework that detail the performance requirements that a sprinkler must conform to. Furthermore, the types of occupations that are generally present within high-rise buildings and the associated hazard classification and requirements are researched. Lastly, miscellaneous requirements that are relevant to this research are also included.

2. **What are the requirements for designing water storage tanks?**

Similarly, requirements for water storage tanks and sprinkler feed systems must be researched. This is done for each framework and includes general design of water storage tanks as well as refill requirements that must be met for the system. Furthermore, placing one or multiple water storage tanks at higher altitude within a building may pose some structural problems which must also be researched.

3. **In which scenarios can gravity-feed systems be applied?**

Based on the results of the previous questions several scenarios are set up to test the efficacy of applying gravity-feed sprinkler systems. This is to test per framework which hazard classifications can be realistically protected by such a system.

4. **How should a gravity-feed sprinkler system in a high-rise building be designed?**

To write the guidelines it is necessary to determine the recommended parameters for designing the gravity-feed systems per scenario. This includes the placement, sizing and refill systems for water storage tanks within the building as well as the sizing of piping within the sprinkler systems to ensure appropriate flow and pressure on the sprinkler heads.

1.7 Research scope

This research is strictly limited to the three normative frameworks: FM Global, NFPA, and NEN. Other normative frameworks exist but fall outside the scope of this research. This is because the chosen frameworks are almost always applied to sprinkler systems within the Netherlands. Rarely, another framework may need to be applied. Should it be desired to use a gravity-fed system in a different normative framework, this research can be used as a method of comparing requirements with the scenarios described per hazard classification. This can provide a cursory insight into the feasibility of applying a gravity-fed system in another normative framework. It will then need to be substantiated further with calculations to confirm applicability.

Furthermore, research is limited to only sprinkler systems. Due to pressure requirements for operating water mist systems, gravity-fed systems cannot reasonably be expected to provide equivalency to conventional pump systems. It may be possible to apply gravity-fed systems to fire suppression foam systems, but this is not a part of the scope of this research. Additional legislative and technical requirements for applying this research to fire suppression foam systems require further investigation. Also, hydrants and hoses are not included in the design of the systems. This is because within the Netherlands, hydrants and hoses are typically connected to the potable water supply and not the sprinkler system.

Lastly, legislative requirements that will be detailed for this research shall only pertain to requirements directly related to the design and operation of sprinkler systems and the sizing, placement, and refill of water storage tanks. Furthermore, any rule or regulation superseded by more specific legislation for sprinkler systems in high-rise buildings will not be part of the scope of this research. Test scenarios created for this research only cover occupancies reasonably expected to be present within a high-rise building. This means that occupancies with large amounts of storage and occupancies containing dangerous substances are not considered.

1.8 Plan of approach

The research is split into a number of chapters which detail the process and results. First is the preliminary literature review which was done into relevant topics to this research, and the methodology used to obtain results (Chapter 2). To create a basis on which to calculate the design criteria for gravity-feed systems, in-depth research was done into the three normative frameworks and the design requirements set by them (Chapter 3). The requirements cover the requirements for sprinklers as well as requirements set for water tanks. Included is also specific requirements set for high-rise buildings. Afterwards, considerations for placing large volume water tanks at height within buildings is described (Chapter 4).

Using the basis set in Chapter 3 it was possible to create the test setup and scenarios. These scenarios were used to calculate the design criteria for sprinkler systems. This includes a mock building which was used to create example floor plans (Chapter 5). Afterwards, using the defined test scenarios it was possible to perform the necessary calculations using SprinkCALC (Chapter 6). This discusses the piping diameters used for calculations as well as the minimum and maximum height difference between gravity-tank and sprinkler zone. With the calculations it was possible to draw conclusions (Chapter 7) and describe recommendations (Chapter 8) for designing gravity-feed systems.

2 Research approach

By outlining already existing research and concepts surrounding the topics involved in this research can it be guided in the appropriate direction. This is done by performing a preliminary literature review into relevant topics and concepts related to this research. This shall form the basis upon which the research shall build and expand to answer the main research question posed in this report (Section 2.1). Afterwards, a methodology can be defined to explain what shall be done to realise the goals of this research (Section 2.2).

2.1 Preliminary literature review

At the centre of this research is the design of sprinkler systems. This literature review intends to highlight important topics related to this design process. Vishnoi (2017) identifies four main steps in this process. Firstly, a preliminary analysis of the building is made. Afterwards, based on the normative framework the design criteria for the sprinkler system are defined. An overview is given of the three normative frameworks that are part of this research (Subsection 2.1.1). Furthermore, the definitions of the design criteria are discussed (Subsection 2.1.2). Thirdly, the network layout of the water distribution is made. For this, the different water distribution system components are defined (Subsection 2.1.3). Lastly, a hydraulic analysis is made of the system to confirm that the system conforms to the design requirements. Furthermore, this literature review discusses the current state of gravity-feed systems for sprinkler operation. This will detail the previous research done, gaps still present on this topic, and how this research contributes to this (Subsection 2.1.4).

2.1.1 Normative frameworks

As previously stated, this research centres around the requirements formed by FM Global, NFPA, and NEN. These frameworks are in many ways similar but differ on a few key points. NEN is the Netherlands Standardization Institute which develops and manages standards in many areas. They are active primarily within the Netherlands but are also part of international standards organisations like the European Committee for Standardization (CEN), CENELEC, International Organisation for Standardization (ISO), IEC, and ETSI (NEN, n.d.). By extent NEN also develops the NEN-EN norms that are interpretations of the European Norms (EN) developed by CEN. These EN standards are mandatory to be implemented by all European member states and may not conflict with local norms and standards (European Commission, n.d.). Furthermore, European EN standards are also synchronized with the international ISO standards via the Vienna agreement. This is to prevent the duplication of effort and reducing time when preparing standards. This means that CEN and ISO standards are jointly developed and implemented to avoid discordancy between the two (CEN-CENELEC, n.d.). Fire safety regulation per NEN is mostly centred around detecting and preventing spread of the fire and allowing the safe escape of occupants in the building. The prevention of spreading of fire pertains the spread within the structure as well the spread to its surroundings.

The NFPA is an American association of loss prevention engineers that are active globally in developing and maintaining standards specifically for fire and life safety. Like NEN, NFPA standards focus on the detection and prevention of spreading of the fire to allow the safe escape of building occupants. NFPA Standards are updated on a three-year cycle. These standards are substantiated by a balanced, volunteer technical committees of experts (Durante, 2022). The committees are comprised of all parties involved such as contractors, insurances representatives, manufacturers, fire protection engineers, fire service officials, and building code officials.

FM Global is a group of commercial property insurance brokers that publish fire safety standards based on NFPA. However, these standards are altered based on loss history and tests conducted in labs by scientists and loss prevention engineers. FM Global are typically the most conservative standards compared to other normative frameworks in the industry (Durante, 2022). The main focus with FM Global standards lies in business continuity and property protection rather than the safe escape of occupants and prevention of spread to surroundings.

2.1.2 Design criteria for sprinkler systems

The design criteria for sprinkler systems dictate the performance requirements that the sprinkler system design must be able to deliver. Below is an overview of terms and definitions relevant to this research. These have been gathered from Vishnoi (2017) and Jevtić (2018) and supplemented from experience.

- **Type of system**

This refers to the type of sprinkler system is applied. Most commonly, a wet system is applied where pipes are filled with water (Jevtić, 2018). However, if sprinklers are applied where there is a risk of freezing temperatures a dry system must be applied. Here, the pipes in the frost-sensitive area must all be pressurized using either dehumidified air or inert gasses. These two system types are both used within this research.

- **K-Factor**

K-Factor is related to the amount of water a sprinkler head can discharge. The K-factor of sprinkler heads is expressed in the letter K followed by a number which specifies the discharge coefficient. The discharge coefficient is the flow of a sprinkler divided by the square root of the pressure. This is expressed as (dm3/min)/bar½ in SI-units.

- **Pressure**

The sprinklers must be operated at a certain pressure to ensure the fire is properly suppressed.

- **Demand Area**

It is expected that when a fire breaks out, the fire load will not exceed a certain area with proper activation and operation of the sprinkler system. When designing a system, only a certain area need be kept in mind.

- **Spray density**

Density is expressed in mm/min/m^2, this is the volume of water the sprinkler must discharge per square meter below it per minute.

- **Spacing between sprinklers**

Spacing between sprinklers is related to maximum area of coverage per sprinkler head. When designing a sprinkler system, the heads may not be further apart than this maximum and may also not exceed their maximum coverage of area they may protect.

- **Sprinkler duration**

Depending on the hazard, the duration during which the sprinklers are operational can change. For low hazard classifications this is often 30 minutes, but the duration can go up to 90-120 minutes.

2.1.3 Water distribution system components

The water distribution system is the system which carries the water from the water tank to the sprinkler heads. This research uses the definitions given by NFPA13 (NFPA, 2021b). Below is an overview of the components found within the water distribution system. Furthermore, Figure 1 shows an isometric view of the water distribution system and its components.

- **Riser**

The riser is a vertical pipe that supplies all sprinkler zones within a system.

- **Feed main**

Feed mains supply the cross mains from the riser. Alarm valves or floor control valves are typically installed on feed mains.

- **Cross main**

Cross mains supply the branch lines and the sprinklers on the branch lines. Sprinklers are sometimes also installed on cross mains.

- **Branch line**

Branch lines directly supply the sprinklers within the system from the cross mains.

- **Alarm valve**

The alarm valve functions to section the building and opens only when the pressure drops due to an opened sprinkler. This valve then sends an alarm signal which is used to alarm the building owner of fire. This valve is often installed on a riser or feed main.

- **Floor control valve**

Floor control valves are used to section off individual floors served by the same alarm valve. This allows individual floors to be closed off in case of maintenance instead of the entire system.

- **Check valve**

A check valve prevents water from flowing back into the system. This valve is combined with the floor control valve to create sections within the same sprinkler zone protected by a single alarm valve.

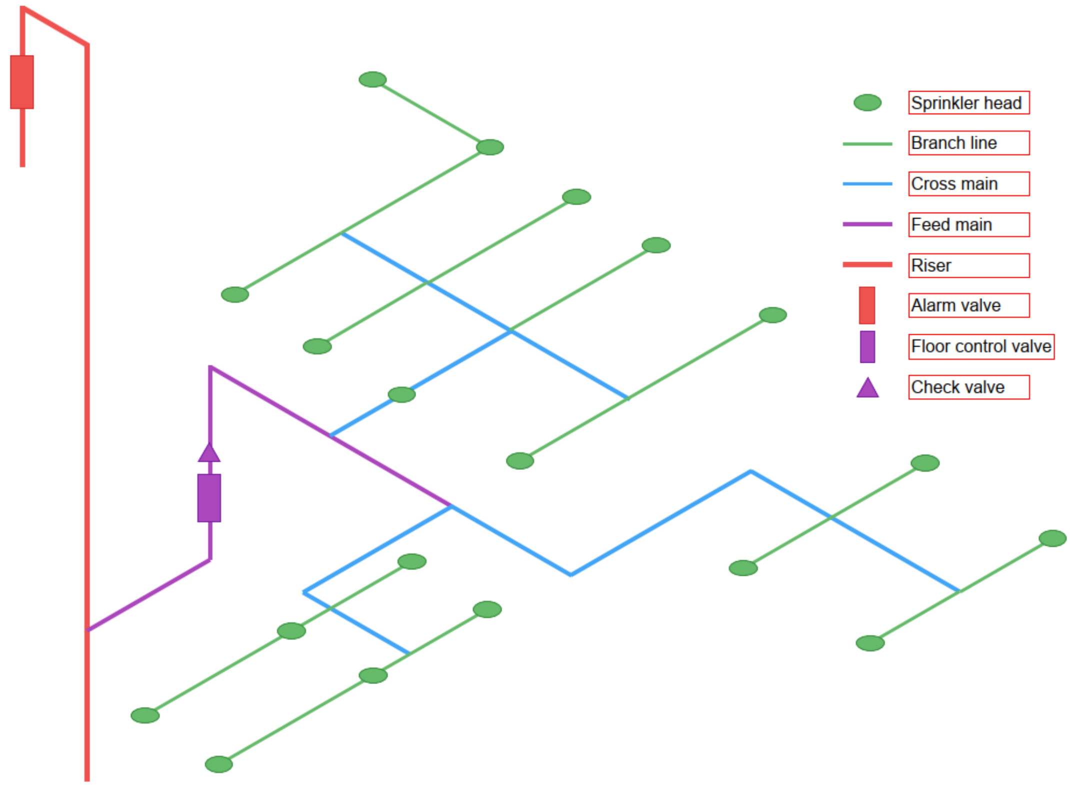

Figure 1: Isometric view of the water distribution system and its components

2.1.4 Current state of gravity-feed systems

Gravity-feed systems are not only applied for fire sprinkler systems, but also has a long history in agrarian applications. Traditionally, this is done by conveying surface sources such as rivers or reservoirs, both natural and artificial, through a network of canals of varying sizes with the use of gravity (Masseroni et al., 2017). This then irrigates the soil without the need for any pumps. This is comparable to the system applied for fire sprinkler systems.

Another way a gravity-feed system has been applied in the agrarian sector is a so-called drip or trickle irrigation system (Raphael et al., 2018). Instead of irrigating the soil of the entire field, this system steadily, at a slow rate, irrigates the area around the root. This system excels in efficiently irrigating crops and reduces the total water consumption by concentrating irrigation to a small area. This is done by placing a water tank overhead above the crops outside the greenhouse and with careful pipe sizing the drip rate is manipulated to constantly spread the correct amount of water. This practice of carefully sizing pipes to control the flow of the system is similar to that used for fire sprinkler systems but can be altered to suit the unique needs of a gravity-feed system compared to the traditional pumped system.

Some normative frameworks have already included some legislation related to gravity-feed systems. Pennel and Popov (2021) provides some insight in the legislative requirements of applying gravity-feed sprinkler systems in high-rise buildings using NFPA. It also includes a theoretical design of a gravity-feed sprinkler system. However, this design is limited only to the placement of water tanks and standpipes. It does not provide any form of design guidelines for pipe sizing and height difference between the sprinklers and water tank. This is also true for the other normative frameworks. The practical design principles and guidelines have yet to be explored. And thus, this research has been performed to gain an overview of all the legislative and technical requirements that must be complied with to apply gravity-feed systems. It will result in design guidelines for NEN, NFPA, and FM Global and include the minimum required height difference between the sprinklers and water tank, and pipe diameters to use for such a system.

2.2 Methodology and phasing

The goal of this research is to gain an in-depth, comprehensive overview of the legislative and technical requirements of applying gravity-feed systems and to create a set of guidelines for the design of such systems. Guidelines are substantiated to show compliance with the three normative frameworks: FM Global, NFPA, NEN. The research is split into four phases. The first phase is the normative frameworks and requirements phase (Subsection 2.2.1). Secondly, is the use case scenarios and setups phase (Subsection 2.2.2). Thirdly, is the feasibility calculation and substantiation phase (Subsection 2.2.3). Lastly, is the design guideline creation phase (Subsection 2.2.4). Table 2 shows an overview of all phases of the research. It includes per phase which sub-questions it answers, the methodologies used, and in which chapters of this report the results of the phase are discussed.

Table 2: Overview of phases and methodology

Phase	Related sub-question(s)	Methodology	Related chapters
Phase I	1, 2	Qualitative research	Ch. 3, 4
Phase II	3	Test scenario creation	Ch. 5
Phase III	3, 4	Hydraulic analysis and data visualisation	Ch. 6
Phase IV	3, 4	NEN-based dimensioning tables	Ch. 6

Furthermore, to show the correlation between report elements within this research a flow chart has been created (Figure 2). It shows per phase the related the chapters and the relation between chapters. Since Chapter 6 spans both Phase III and Phase IV it has been split up into its respective sections. Each arrow represents the output of a chapter which is used in another chapter. A detailed version of this flow chart including the descriptions of these outputs can be found in Appendix A1.

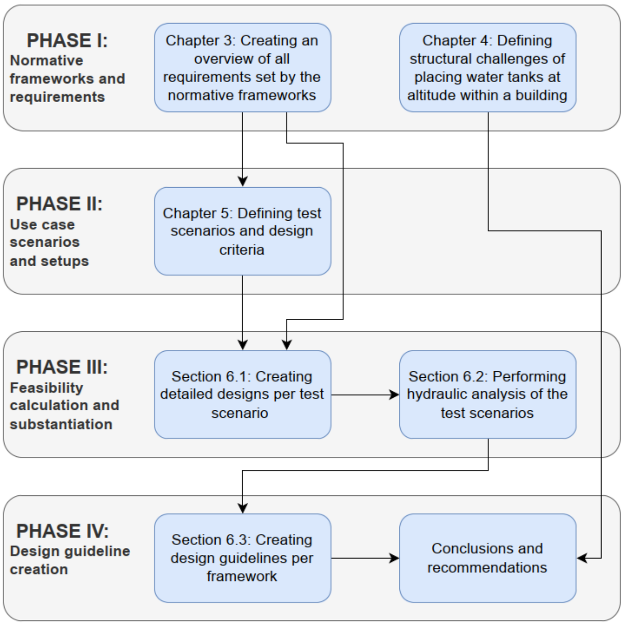

Figure 2: Simplified flow chart of report elements (Detailed version can be found in Appendix A1)

2.2.1 Phase I: Normative frameworks and requirements

The first phase consisted entirely of qualitative research. The goal was to create a complete overview of the requirements that apply to designing sprinkler systems based on FM Global, NFPA, and NEN. For this, all relevant documents were gathered and reviewed to determine all requirements that must be met for designing sprinkler systems in high-rise buildings and also requirements for gravity-feed systems. Furthermore, this method also extended to finding the requirements that apply to water storage tanks, refill requirements that must be met and other miscellaneous requirements that were deemed to be within scope of this research.

Secondly, during this phase the building physics department within Royal HaskoningDHV was consulted with to discuss the structural limitations that may need to be accounted for when placing large volume water storage tanks at high altitude within buildings. This adds a large amount of weight that may possibly exceed limitations in existing buildings or may need to be considered when designing sprinkler systems for buildings still in the design phase. This was done informally not through interview but rather through conversation with experts on this matter. This phase answers Sub-Questions 1 and 2.

2.2.2 Phase II: Use case scenarios and setups

After defining all the requirements that are set by the normative frameworks, it is necessary to set up several scenarios that will be used to substantiate the feasibility of applying a gravity-fed sprinkler system. This is related to Sub-Question 3. Multiple scenarios with different occupations and other parameters have been created based on the hazard classifications. Then, per scenario it is stated the requirements the sprinkler system must conform to based on all three normative frameworks. These scenarios are used in the following phase to calculate the demands of the systems in each scenario and whether a gravity-fed sprinkler systems could provide the necessary coverage.

2.2.3 Phase III: Feasibility calculation and substantiation

Using the scenarios created in the previous it became possible to substantiate the feasibility of applying gravity-fed sprinkler systems or show its limitations. This answers Sub-Questions 3 and 4. To do so, SprinkCALC was used to perform quantitative research. This is a specialised software package designed by Johnson Controls for digitally designing and testing sprinkler systems. It is also the only UL-listed software capable of calculated fluid delivery times. It considers many factors including but not limited to pipe diameters, gravity, pipe roughness, sprinkler K-factors, spray density, and required pressure on sprinkler heads. This makes it an ideal solution calculating the pressure required from the system to operate the sprinkler according to the relevant hazard classification per normative framework. From this, it was also calculated the required height difference between the water storage tank and the sprinkler zone. With these calculations it was possible to create a complete overview of the hazard classifications that can be practically serviced using a gravity-fed system as well as all the design parameters that need to be considered for this. This includes all piping diameters used from feed mains, to branch lines. From this, it became possible to write design guidelines that can be used in the future to speed up the designing process for designing gravity-fed sprinkler systems.

2.2.4 Phase IV: Design guideline creation

Lastly, the design guidelines were created. This was done based on the answers to Sub-Questions 3 and 4. The results from the hydraulic analysis were then incorporated into a table for each normative framework which shows the recommended pipe diameters for initial design of gravity-feed sprinkler systems. The tables are designed based on similar pipe sizing tables provided for traditional pumped sprinkler systems by NEN in NEN12845:2015 + NEN1073:2018 (NEN, 2018).

3 Normative frameworks and requirements

After the preliminary studies are performed on the location to be protected by a sprinkler system, the legislative requirements can be determined. A decision must be made on which framework will be used, as it is not allowed to cherry-pick requirements between multiple frameworks. This means that often a normative framework least stringent for the specific scenario is chosen. Another reason a specific framework may be chosen for example, is that there are atria present that exceed the limits of NEN and NFPA. In such cases FM Global may be chosen as FM Global allows spaces up to 30 meters in height compared to 12 and 15 meters for NEN and NFPA respectively.

The system design is determined in a backwards fashion. This means that first the requirements for the sprinklers and the design requirements are determined (Section 3.1). Afterwards, the water supply system requirements are determined (Section 3.2). This includes the water storage tanks, any pumps, and the piping which leads to the sprinklers. Lastly, the results of this chapter and how it is used in this research is discussed (Section 3.3). The results of this chapter form the basis of the answers to Sub-Questions 1 and 2 as part of Phase I of the research.

3.1 Sprinkler system design requirements

Determining the sprinkler system design requirements is done in two steps. The first is determining the hazard classifications present within the building (Subsection 3.1.1). From the hazard classifications, the design requirements can then be determined (Subsection 3.1.2). Using these requirements, the use cases can be set up to calculate the viability of applying a gravity-feed system.

3.1.1 Hazard classifications

As said before, the first step in determining the design requirements for sprinklers is to determine the hazard classifications present within the building. Each normative framework has its own variation on hazard classifications with a different name. For clarity, the term hazard classification will be used instead of the different names the normative frameworks each give.

Each hazard classification has an associated set of design requirements for sprinkler systems. These design requirements become more stringent with heavier hazard classifications. Thus, the hazard classifications form the basis upon which the sprinkler system will be designed. The hazard classifications provided by each normative framework are very similar. The major difference between the frameworks is the amount of hazard classifications it specifies, though the hazard classifications divide the same spectrum from low fire hazard to a very high fire hazard. FM Global divides this spectrum over four different hazard classifications. NEN and NFPA instead divides this spectrum over six hazard classifications.

Each framework also gives a number of examples of occupations and which hazard classification is associated with it. Most of these examples are given a similarly stringent hazard classification by all normative frameworks. However, there are some exceptions where one normative framework is notably less stringent compared to the others. For example, parking garages have less stringent hazard classification compared to NFPA or FM Global. Another example are cinema theatres, which have the least stringent hazard classification by NFPA but a much more stringent hazard classification by NEN. Thus, depending on the way a building is occupied a choice may be made to choose the normative framework which has the least stringent hazard classifications for those specific occupancies.

A table is created for each normative framework which shows the different hazard classifications that the framework specifies with a description of the level of fire hazard associated with it. For each hazard classification a small list of occupancies is given which are associated with that hazard classification. The test scenarios will be based on these example occupancies, so no assumptions need to be made on which hazard classification is applicable if the framework does not include the occupancy in its examples.

NEN hazard classifications

Hazard classifications are called hazard classes in NEN-EN12845:2015 + NEN1073:2018 (NEN, 2018). The hazard classifications include Light Hazard (LH), Ordinary Hazard (OH) Group 1, Group 2, Group 3, and Group 4, and High Hazard Process and Storage. High Hazard occupancies fall outside the scope of this research as this classification relates to occupancies not reasonably expected to be present within high-rise buildings. Below is an overview of all hazard classifications as per NEN with example occupancies (Table 3).

Table 3: Hazard classifications per NEN-EN12845:2015 + NEN1073:2018 with examples (NEN, 2018)

Hazard classification		Description	Examples
Light Hazard		Occupancies with low combustibility and low fire load of contents. There may be no storage of goods. Compartments within this classification may not exceed 126m^2 and must be fire resistant up to 30 minutes.	Schools, offices, jails, residential
Ordinary Hazard	Group 1	Occupancies with low to moderate combustibility and low fire load of contents. There may be no storage of goods.	Hospitals, hotels, restaurants, offices
	Group 2	Occupancies with low to moderate combustibility and fire load of contents. There may be no storage of goods.	Bakeries, parking garages, laundries, laboratories, museums
	Group 3	Occupancies with moderate combustibility and fire load of contents. Storage of goods is permitted with limited height and area of storage.	Furniture stores, sewing workshops, woodworking, Shopping centres
	Group 4	Occupancies moderate combustibility and moderate to high fire load of contents. Storage of goods is permitted as per OH Group 3. Occupation must be treated as High Hazard Storage, should storage exceed those limitations.	Cinemas and theatres, concert halls, Film- and TV-studios
High Hazard, Process / Storage		Occupancies with high combustibility and fire load of contents. Falls outside the scope of this research.	N.A.

NFPA hazard classifications

The equivalent of hazard classifications of NFPA are called occupancy classifications. The hazard classifications include Light Hazard, Ordinary Hazard Group 1 and Group 2, Extra Hazard (EH) Group 1 and Group 2, and High-Piled Storage. Occupancies classified as Extra Hazard or High-Piled Storage are not reasonably expected to be present within high-rise buildings and are thus considered outside the scope of this research. Below is an overview of the hazard classifications with examples of occupancies per NFPA (Table 4).

Table 4: Hazard classifications per NFPA13 with examples (NFPA, 2021b)

Hazard classification		Description	Examples
Light Hazard		Spaces with low quantity and combustibility of contents. Storage of goods is not permitted within these occupancies.	Clubs, hospitals, offices, residential, theatres, restaurant seating areas
Ordinary Hazard	Group 1	Spaces with moderate quantity and low combustibility of contents including stockpiles of contents with low combustibility that does not exceed 2.4 meters in height. Storage of limited goods is permitted up to a maximum 3.7 meters and 3.0 meters in height respectively.	Bakeries, laundries, restaurant service areas, mechanical rooms
Ordinary Hazard	Group 2	Spaces with moderate to high quantity and combustibility of contents. It includes limited storage of good with moderate rates of heat release that does not exceed 3.7 meters in height and contents with high rates of heat release that does not exceed 2.4 meters in height.	Parking garages, dry cleaners, mercantile, post offices
Extra Hazard, High-Piled Storage		Extra Hazard encompasses spaces with very high quantity and combustibility of contents. LH, OH, and EH occupancies that exceed miscellaneous and low-piled storage limitations are classified as High-Piled Storage. These classifications fall outside the scope of this research.	N.A.

FM Global hazard classifications

Unlike NEN and NFPA, FM Global only provides hazard classifications for nonstorage occupancies. Design requirements for storage occupancies are instead determined using the classification of commodities present within the occupancy and the manner of storage, however this falls outside the scope of this research. There are three hazard classifications per Datasheet 3-26 paragraph 2.2.2 (FM Global, 2021b). The classifications are Hazard Category 1 (HC-1), Hazard Category 2 (HC-2), and Hazard Category 3 (HC-3). Below an overview is given of each hazard classification with example occupancies (Table 5).

Table 5: Hazard classifications per FM Global with examples (FM Global, 2021b)

Hazard classification	Description	Examples
Hazard Category 1	Areas with an overall light combustible loading. Storage of limited goods in limited quantities is allowed in this classification	Residential, offices, hospitals
Hazard Category 2	Areas with moderately continuous presence of combustible loading. This includes combustibles in processes and operations of moderate hazard. Storage of less limited goods in limited quantities is allowed in this classification	Machine shops, woodworking, electronic assembly, retail, theatres, food production, bakeries
Hazard Category 3	Areas with a generally continuously present combustible load. Storage of goods is allowed in this classification in limited quantities.	Loading docks, parking garages, exhibition halls
Storage	Any occupancy with storage exceeding limits for incidental and low-piled storage within nonstorage occupancies. Falls outside the scope of this research.	N.A.

3.1.2 Design requirements for sprinklers

Using the hazard classifications as specified by the frameworks, the sprinkler design requirements can be determined. For each normative framework the same two tables are filled in for easier comparison between frameworks. The first table shows:

- The spray density, which is the flow the sprinkler heads must deliver per square meter expressed in millimeters per minute.
- The demand area, which is the expected area in which sprinklers will activate in case of fire.

The second table shows additional requirements:

- The maximum section area is a limitation imposed to limit the floor area that a single system connected an alarm valve may protect.
- Water delivery time is the maximum time it may take for water to discharge from sprinklers at the design pressure and density for dry pipe systems.
- Sprinkler spacing in linear distances between sprinkler heads and the area protected per sprinkler.
- The minimum pressure that must be present to operate the sprinklers. In most cases complying with the density and demand area requirements will lead to a higher pressure on the sprinkler.
- The K-factor to be used for the sprinklers. NFPA and FM Global instead give a minimum K-factor to be used instead.

NEN design requirements

Sprinkler density and demand area requirements are stated in NEN12845:2015 + NEN1073:2018, hereafter referred to as NEN-EN12845, Section 7.1 Table 3 (NEN, 2018). All hazard classifications relevant to this research have been gathered and shown in an overview below (Table 6). Hazard classification HHP1 has been included as dry pipe systems in OH4 areas must be designed according to HHP1. Appendix E of NEN-EN12845 states that in buildings height difference of more than 45 meters from the lowest to highest sprinkler, the sprinkler system must at minimum be calculated for OH3.

Table 6: Sprinkler density demand area requirements per NEN-EN12845:2015 + NEN1073:2018 Table 3 (NEN, 2018)

Hazard Classification	Spray Density (mm/min)	Demand Area (m^2) Wet systems	Demand Area (m^2) Dry Pipe systems
LH	2.25	84	Use OH1
OH1	5	72	90
OH2	5	144	180
OH3	5	216	270
OH4	5	360	Use HHP1
HHP1 (Only for OH4 dry)	7.5	N.A.	325

Other design requirements can also be found within the same document. These have been compiled and shown in the overview below (Table 7). Maximum section area was taken from subsection 11.1.3, water delivery time from subsection 11.2.2, sprinkler maximum spacing from section 12.2, minimum spacing from section 12.3, minimum working pressure from subsection 13.4.4, and sprinkler K-factor form subsection 14.2.1.

Table 7: Other design requirements for sprinklers per NEN-EN12845:2015 + NEN1073:2018 (NEN, 2018)

Hazard Classification	Maximum section area (m^2)	Water delivery time	Sprinkler spacing			Minimum pressure (bar)	K-factor
			Linear		Area		
			Min. note1	Max.			
Light Hazard	10.000	90 seconds on most remote sprinkler	2.0 m	4.6 m	21 m^2	0.7	K57
Ordinary Hazard	12.000	60 seconds on most remote sprinkler	2.0 m	4.0 m	12 m^2	0.35	K80, K115

NFPA design requirements

Like NEN, NFPA states design requirements for sprinklers with density and demand area. However, unlike NEN, instead of increasing the demand area with increasing hazard classification NFPA increases the density requirements. Requirements were taken from NFPA13 paragraph 19.2.3.1.1. Furthermore, paragraph 19.2.3.2.5 states that for dry pipe systems, that demand area must be increased by 30 percent (NFPA, 2021b). An overview of design requirements is shown below (Table 8).

Table 8: Sprinkler density demand area requirements per NFPA13 (NFPA, 2021b)

Hazard Classification	Spray Density (mm/min)	Demand Area (m^2) Wet system	Demand Area (m^2) Dry Pipe systems
LH	4.1	140	182
OH1	6.1	140	182
OH2	8.1	140	182

Other design requirements can also be found within the same document. These have been compiled and shown in the overview below (Table 9). Maximum section area was taken from Subsection 4.4.1, water delivery time from Subsection 8.2.3, sprinkler spacing from paragraph 10.2.4.2.1, and minimum sprinkler K-factor form Subsection 9.4.4.

Table 9: Other design requirements for sprinklers per NFPA13 (NFPA, 2021b)

Hazard Classification	Maximum section area (m^2) note 1	Water delivery time Dry Pipe systems	Sprinkler spacing			Minimum pressure (bar)	Minimum K-factor
			Linear		Area		
			Min.	Max.			
Light Hazard	4830	60 second on most remote sprinkler	2.0 m	4.6 m	20 m^2	0.5	K80
Ordinary Hazard Group 1, 2	4830	50 seconds on two most remote sprinklers	2.0 m	4.6 m	12 m^2	0.5	K80

Note 1. The maximum protection area specified by NFPA is based on a maximum floor area per floor in a building serviced by one riser. This means that one section may supply the entire building if individual floors do not exceed 4830 m^2 in area. However, maximum working pressure limits must still be upheld. Each floor must also be supplied with a control valve such that the entire system does not need to be taken out of service in case of maintenance. Furthermore, a flow switch, test and drain connection must be placed downstream of each floor control valve for signalling and maintenance.

FM Global design requirements

The design requirements as per FM Global both increase in density and demand area with increasing hazard classifications. Additionally, design requirements increase depending on the ceiling height. There are four groups of ceiling heights for density and demand area. The first is for spaces with a ceiling height up to 9 meters. As most occupancies reasonably expected to be present within a high-rise building fall in this group the design requirements are shown for this group. An exception to this is atria which can reach above 9 meters in height. The requirements are taken from paragraph 2.3.1.10 of Datasheet 3-26 (FM Global, 2021b). An overview is given below (Table 10).

Table 10: Sprinkler density / demand area requirements per Datasheet 3-26 (FM Global, 2021b)

Hazard Classification	Spray Density (mm/min)	Demand Area (m^2) Wet systems	Demand Area (m^2) Dry pipe systems
Hazard Category 1	4	140	140
Hazard Category 2	8	230	330
Hazard Category 3	12	230	330

Other design requirements can also be found Datasheets 2-0 and 3-26. These have been compiled and shown in the overview below (Table 11). From Datasheet 2-0 Maximum section area was taken from paragraph 2.2.1.4, sprinkler spacing from paragraph 2.5.2.3.1, minimum working pressure from paragraph 2.5.1.1.2, and minimum sprinkler K-factor from paragraph 2.5.2.1.1. From Datasheet 3-26 water delivery time was taken from Subsection 11.2.2 (FM Global, 2021b).

Table 11: Other design requirements for sprinklers per FM Global data sheets

Hazard Classification	Maximum section area (m^2) note 1	Water delivery time Dry Pipe systems	Sprinkler spacing				Minimum pressure (bar)	Minimum K-factor
			Linear (m)		Area (m^2)			
			Min.	Max.	Min.	Max.		
HC-1	No area limit	60 seconds on the single most remote sprinkler or 40 seconds on the most remote four sprinklers with two sprinklers on two branch lines	2.1	4.6	6.0	20.9	0.5	K80
HC-2			2.1	4.6	6.0	12.1	0.5	K80
HC-3			2.1	3.7	6.0	9.3	0.5	K80

Note 1. FM Global does not specify a specific floor area that may be protected by any one section. Rather, the system must be able to fulfil the hydraulic requirements of the design. For dry pipe systems this also requires the system to fulfil the water delivery time requirements. For wet systems, waterflow alarm devices (for example alarm valves or flow switch) must be placed such that an alarm activates at the latest 60 seconds after activation of any one sprinkler.

3.2 Water supply requirements

Water storage tanks must be sized to be able to provide enough water for the entire duration of protection to sprinkler zones downstream of it. This means that tanks are sized to the demands of the sprinkler zone with highest water demand calculated using hydraulic analysis. Furthermore, the water storage tanks must also be resupplied with water within a certain time frame. This must be accomplished within eight hours. This timeframe may be increased to 36 hours; however, this must be approved by the Authority Having Jurisdiction (AHJ) and therefore more stringent requirements may be imposed.

There are several ways in which can complied to the refill requirements. A connection can be made to the utility water source, pumped from a refill pump, filled from a gravity-tank above, or pumped from a tanker truck. Any of these methods may be applied so long as it can comply with the time limit for refill. Different solutions may be chosen based on the height of the building and other factors. Possible solutions for complying to this requirement in a cost-effective manner will be explored in Section 5.1.

Pipes used for sprinkler systems must also comply with certain requirements. Pipes must be of at least a certain diameter based on the normative framework and hazard classification. Pipes diameters are expressed in Diameter Nominal (DN) in millimeters. Furthermore, pipes used for dry pipe systems must be pitched in parts that are filled with inert gasses or dehumidified air. For all frameworks this must be a pitch of 2 millimeters height per meter of pipe. For branch lines this is 4 millimeters per meter. Below is an overview of general water supply requirements for all normative frameworks (Table 12). Lastly, per framework specific requirements are noted including high-rise specific requirements.

Table 12: General water supply requirements

<table>
<tr><th>Framework</th><th>Hazard Class.</th><th>Sprinkler duration</th><th>Refill time</th><th>Min. pipe size</th><th>Pipe pitch</th></tr>
<tr><td rowspan="2">NEN</td><td>LH</td><td>30 min.</td><td rowspan="5">8 hours</td><td>DN20</td><td rowspan="5">Branch lines:
4 mm/m

Mains:
2 mm/m</td></tr>
<tr><td>OH</td><td>60 min.</td><td>DN25</td></tr>
<tr><td rowspan="2">NFPA</td><td>LH</td><td>30 min.</td><td rowspan="2">DN25</td></tr>
<tr><td>OH</td><td>60 min.</td></tr>
<tr><td>FM Global</td><td>All</td><td>60 min</td><td>DN25</td></tr>
</table>

NEN water supply requirements

Appendix E of NEN-EN12845 states specific requirements for water supplies in high-rise buildings (NEN, 2018). The maximum height difference between the lowest and highest sprinkler connected to the same alarm valve may not exceed 45 meters. This means that floors connected to the same water tank must be divided over different alarm valves covering at maximum 45 meters in height.

NFPA water supply requirements

In very tall buildings, each sprinkler zone must be supplied by at least two tanks as per NFPA20 Subsection 5.6.1 (NFPA, 2021a). For this, a tank may be divided into compartments that function as individual tanks. Total volume of all tanks or compartments must be sized to be sufficient for the full demand of the sprinkler zone it supplies with a minimum of 50 percent of the demand available with any one tank out of service. Each tank or compartment must also be provided with an automatic and manual refill valve which must be sized and arranged to independently supply the sprinkler system. Refill connections must also be interconnected.

FM Global water supply requirements

Datasheet 1-3 (FM Global, 2013) specifies in paragraph 2.2.4.1 that in buildings taller than 128 meters, a minimum of dual risers must be installed for every sprinkler zone. This is to prevent adjacent floors from being fed from the same riser by alternating the feeding riser per floor. These risers must be placed within stair enclosures, at distance of at minimum half the diameter of the floor to be protected and is measured in a straight line between the risers.

FM Global specifies for high-rise buildings that sprinkler zones should be limited to a maximum of 85 meters vertically and each zone requires a separate fire pump (FM Global, 2021a). For sprinkler zones beyond 85 meters above the pump or below the gravity tank high-pressure piping and fittings must be provided that are rated for the increased pressure on the lower floors of the building. Working-pressure rating of the pipes can be reduced on the higher floor as elevation decreases the static pressure in the pipes.

According to Datasheet 3-2 paragraph 3.6.1 (FM Global, 2022b) risers for gravity tanks must be sized based on the capacity of the tank. For tanks with a capacity up to 94.6m^3 the risers should be at minimum DN150. For tanks between 114m^3 and 378m^3 the riser must be at least DN200. Lastly tanks above 378m^3 require risers of at least DN250. These sizes are just minimums. Depending on the situation larger sized pipes may be required to meet the necessary pressure and flow of the system. Optimal pipe diameters can be acquired with the help of hydraulic analysis. Smaller pipe diameters may be used granted that hydraulic analysis shows the sprinkler system meets the requirements.

3.3 Legislative requirement discussion and further use

On some aspects the requirements set by the three frameworks are quite similar. However, they differ on the approach taken to scaling sprinkler system protection levels with increasing hazard classifications. NEN scales by increasing the demand area while keeping the spray density consistent. NFPA does the inverse, scaling up by increasing the spray density while keeping the demand area the same. FM Global instead takes a combined approach scaling both spray density and demand area with increasing hazard classifications. Though the approach to scaling is different, NEN and NFPA are similarly stringent in their requirements. Due to the combined approach FM Global takes, it is thus also more stringent compared to NEN and NFPA.

On the lightest hazard classification, NEN is the least stringent of the three however due to the reduced spray density and demand area. Though, this is slightly offset by the increased minimum pressure requirement. However, when it comes to high-rise buildings NEN becomes more stringent than NFPA. As a minimum hazard classification of OH3 is enforced for buildings with a height difference greater than 45 meters between the lowest and highest sprinkler. Thus, it can be said that for high-rise buildings NFPA is the least stringent framework to use.

The requirement tables shown in this chapter are used further in this research for the test scenarios and detailed designs. Each test scenario centres around an occupancy with an associated hazard classification from the tables in Subsection 3.1.1. The design requirements for the test scenarios are extracted from the legislative requirement tables in Subsection 3.1.2. The design requirements are then used to create the detailed designs for the hydraulic analysis.

4 Structural limitations for placing water storage tanks at altitude

For gravity-feed systems to function one or more water storage tanks must be placed at altitude within the building. However, this introduces the issue of structural limitations that must be kept in mind when doing so. A large volume of water imposes an equally significant weight that must be supported by the structure below and surrounding it. The structure which supports other floors without this additional load may not be sufficient to support the load which the water storage tank introduces. Therefore, additional measures may need to be taken to account for this. Within RHDHV a constructor was consulted for additional insight into this issue. This chapter aims to highlight the considerations which the constructor states must be taken into account when designing the structure to support the water storage tanks (Section 4.1), and the possible solutions that may be considered to counteract this issue (Section 4.2). It is part of Phase I of this research and helps to answer Sub-Question 2.

4.1 Considerations when designing the structure

Structures must be designed to bear the loads that are put on it. Two of such loads are the dead and live loads. The dead load is a structural load of a constant magnitude over time. This includes weight of structural members such as walls, floors, columns, as well as the weight of fixtures permanently attached to the structure (Udoeyo, 2023). Live loads are loads which are moveable or temporarily affixed to the structure. In this case, the water tank would be a dead load as it is attached to the structure. The water in the tank is a live load as it can move independently from the structure. From a constructor consulted within RHDHV and Barendse & Schnater (2001) it was given that as a rule of thumb a floor is designed to withstand a combined dead and live load of $15kN/m^2$. This is often enough to support the fluctuating loads of changes within the office space and people. However, water in large quantities can easily exceed the floor loads, as water exerts $10kN/m^2$ per meter in height. This means a water column of four meters in height exerts $40kN/m^2$ of force on the structure which supports it.

This means that the rule of thumb cannot be applied to the local structure that must support the water storage tanks. Instead, additional measures must be taken to strengthen the structure and validate the floor loading limitations. This also means that it may be quite difficult to outfit an existing structure with a gravity-feed system without major overhaul to the load-bearing members surrounding the gravity tank.

Lastly, the placement of large volumes of water in tanks at height in a building can pose a problem to building stability in case of dynamic loading of the structure such as in the case of an earthquake. A water tank rigidly affixed to a building may instead increase the amplitude of oscillations of the building which negatively impacts stability. This effect can be reduced with the installation of subdividers within the tank which minimizes the sloshing effect. When designing a gravity-feed system within an area at risk for earthquakes, this must be taken into consideration.

4.2 Solutions to support water storage tanks

To counteract the forces exerted by water in the water tanks, a few possible solutions can be considered. The first is to utilise columns to create a structural box for a water tank. Between the columns load-bearing dividing walls can be placed that strengthen the structure around it so that the floor may be able to bear a greater load.

Alternatively, it may be decided to reduce the height of the water tank to reduce the loading per square meter. This means that the water tank is instead over a much larger floor area. This may be disadvantageous as it uses a lot of floor area that could otherwise be occupied by residences or offices. However, with the lower load imposed on the structure, less needs to be invested in strengthening it.

5 Use cases and test scenarios

Using the requirements gathered in the previous chapters it is possible to create several test scenarios to calculate the minimum and maximum height differences between sprinklers and water tank, and pipe diameters. Each test scenario is made to cover a type of occupancy which could reasonably be present within a high-rise building. Together, the test scenarios will cover all hazard classifications of each framework so that guidelines can be written. The same scenarios will be applied to each normative framework so that a comparison can also be made between the different frameworks.

First the test building that the scenarios will be applied to will be detailed including recommendations for refill systems for compliance will requirements (Section 5.1). Afterwards, six different test scenarios have been created to calculate the constraints for applying gravity-feed systems. Each scenario is applied to each framework and shall contain a clear overview of the design criteria for each specific scenario (Section 5.2). Lastly, the findings of this chapter are discussed and the further use of the scenarios are explained (Section 5.3). This is part of Phase II of this research and helps to answer Sub-Questions 3 and 4.

5.1 Mock building and setup

The objective of the test scenarios is to calculate the minimum and maximum height difference between the water tank and sprinkler zone. Furthermore, the piping diameters of all piping leading from the water tank to the sprinkler heads will also be determined. To calculate this a mock building and setup is made which will be filled per scenario to create a representation of the scenario within a real building. The basic design of the mock building which is used for the calculations is first discussed (Subsection 5.1.1). Another part of the setup is also the placement of the water tanks and the refill setup which is used to resupply the water source within the required timeframe. Guidance and considerations for placement and refill will be discussed (Subsection 5.1.2).

5.1.1 Mock high-rise building

For the mock building, a simple design was made. This design is used only to illustrate how a high-rise building may look and has been designed based on experience and has been simplified. The building is of a rectangular shape of 73 meters long and 29,8 meters in width. Columns are spaced 7,2 meters apart. Such spacing is often used with building design. This is an assumption made on the basis of multiple experts within RHDHV, but no official document has been found. Every floor is of the same base dimensions but can be further detailed in the test scenarios to show a floor plan of the occupancy to be protected. Detailed drawings of the basic design can be found in Appendix A2.

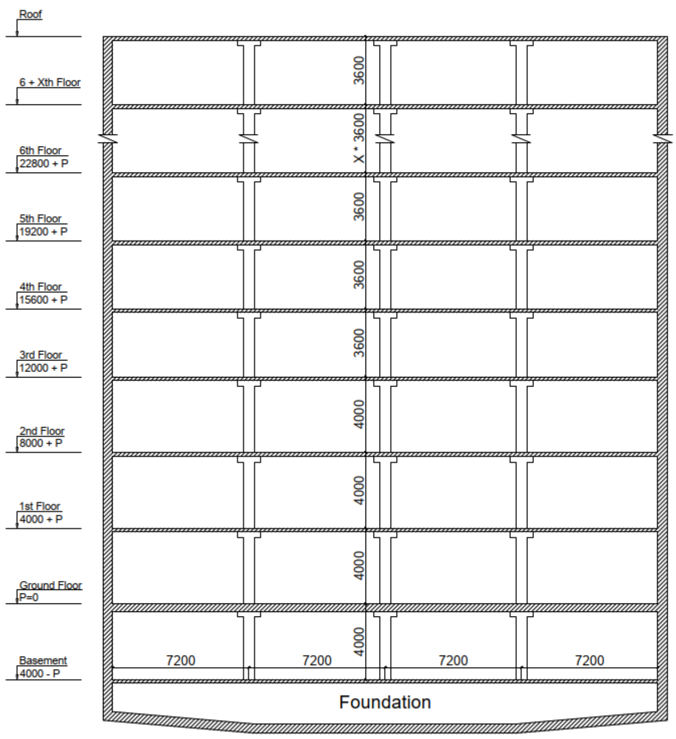

Figure 3: Mock building cross-section (enlarged version can be found in Appendix A2)

Each floor up to the third floor is 4 meters in height, above this each floor is 3,6 meters. For the purposes of the calculations the height of the building is not set. Instead, X number of floors can be used which are also 3,6 meters in height. Figure 3 is a cross-section of the mock building to show a basic overview of a high-rise building.

Each floor contains one staircase around the middle of the floor which goes from the bottom to the top of the building (Figure 4). Adjacent to the staircase is also a utility room which contains the sprinkler system riser and floor control assembly. The floor control assembly consists of a control valve so that only one floor needs to be shut off in case of maintenance. Furthermore, the assembly contains a flow switch to signal the activation of the sprinkler system per floor, and an accompanying test and drain connection.

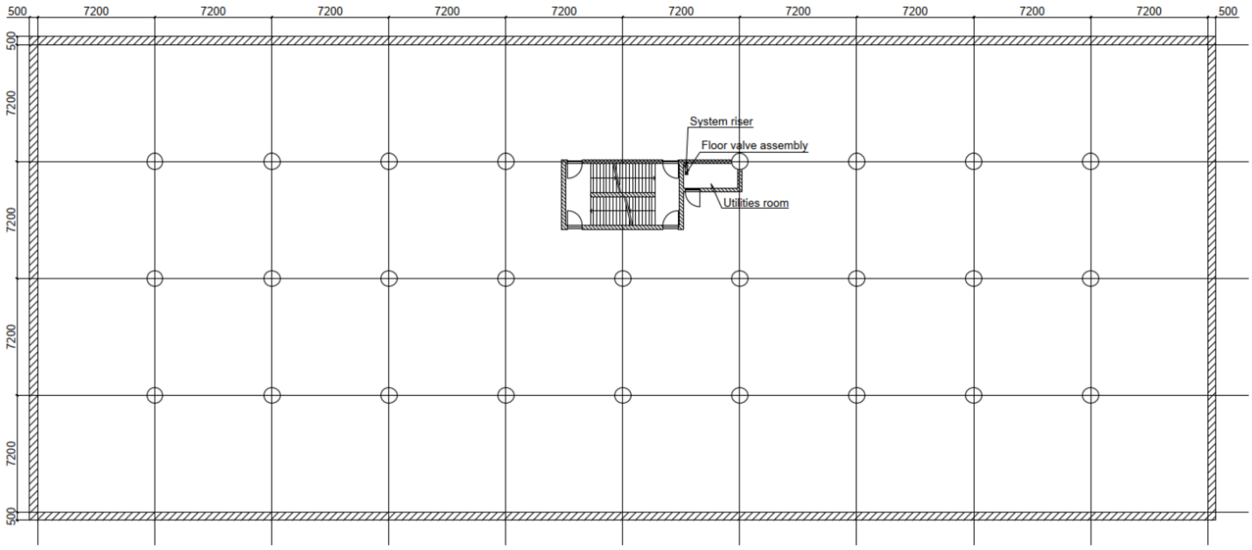

Figure 4: Basic floor plan of the mock building (enlarged version can be found in Appendix A2)

5.1.2 Water tank placement and refill setup

For the purposes of calculations, the water tank is placed on the top floor below the roof, above the sprinkler system riser that runs within the utility rooms. For application to a real building, it is advised to keep in mind the considerations detailed in Chapter 4. The structure must be strengthened locally to support the additional load of the water tank. Furthermore, it is advised to place the water tank in a strategic location such that it can easily be accessed by personnel in case of inspection and maintenance. In a building where multiple water tanks are present which serve different floors, it is advised to place the tanks as such that the higher water tank can supply water to the first floors which the lower water tank cannot serve. This allows for all floors except for the topmost floors to be entirely supplied by water tanks without the need for additional fire pumps (Figure 5).

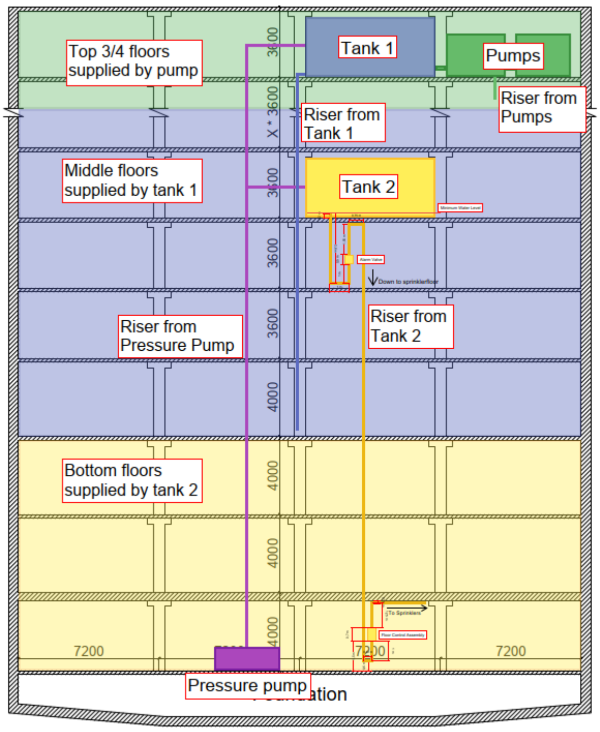

Figure 5: Example water tanks and pump setup

There are two refill connections to be made per water tank. The first is a 75 litre per minute connection to the potable water supply. This connection is not meant to supply the water for refill within eight hours. Rather, this connection is to refill the tank due to small losses of water due to possible leakage or system tests that must be performed. The second connection is a larger connection that is meant to supply the water for complete refill of the tank. This connection can be made in two ways.

The first is a separate connection to the water main for the building at the bottom. However, the water main cannot supply the required pressure to overcome the static pressure losses up to the top floor. To this end, a small electric pressure pump can be added to overcome the static pressure losses. Such a pump is also designed with an extra pump for a fail-safe condition. This connection can then in case of calamity supply the required flow to comply with refill times. Should the building exceed the pump capacity for the pressure pump, another pump set can be placed higher in the building with a break tank between to create a buffer.

Secondly, tank trucks can be used to bring the required volume of water and pump it up to the water tanks. However, these trucks are usually limited to a working pressure of 16 bar and can thus only pump up to 160 meters high. Furthermore, this means that multiple trucks must be parked outside the building over the span of multiple hours.

5.2 Scenario design criteria per framework

Using the test setup, six different scenarios will be applied to test the constraints of gravity-feed systems. Each scenario depicts a specific occupancy which can reasonably be expected to be present within a high-rise building, and the design criteria which a sprinkler system must fulfil to protect it. The six scenarios are chosen so that all hazard classifications are covered, and that the occupancy is named within the examples list of the hazard classification tables of all normative frameworks as shown in Subsection 3.1.1. This is so design guidelines can be written for each framework per hazard classification and no assumptions need to be made as to the hazard classification of an occupancy within a specific normative framework. The six scenarios are:

- **Scenario 1: Residential**

The upper floors of high-rise buildings often contain numerous apartment dwellings. It covers the lightest hazard classifications for all normative frameworks.

- **Scenario 2: Offices**

Like residential, the upper floors are also often used as office space. This scenario is chosen to show the difference between LH and OH1 of NEN, as NFPA and FM Global use the same hazard classification.

- **Scenario 3: Underground parking garage**

Very often high-rise buildings contain one or multiple basement floors which are used as parking for occupants. These floors are often left unheated and thus require a dry pipe system to protect it.

- **Scenario 4: Grocery store**

The ground floor of high-rise buildings is often used to house shops. This may include a grocery store for occupants. This design also covers the higher hazard classes of the normative frameworks.

- **Scenario 5: Bakery**

The design for scenario 4 and 5 shall be combined to resemble the ground floor used for multiple different shops. The bakery has a lighter hazard classification than the grocery store.

- **Scenario 6: Cinema theatre**

Lastly, the cinema theatre was chosen to show the difference between NFPA and the other frameworks as it specifies a much lower hazard classification. It also covers the highest hazard classification for NEN.

The goal is to calculate the technical requirements for such systems as well as show the differences in stringency between frameworks for the same occupancy. The design criteria include: The minimum and maximum height difference between the sprinklers and water tank, as well as the pipe diameters for the water distribution system per scenario.

Scenario 1: Residential

The first scenario covers the residential areas that are present on the top floors (Table 13). This also covers the lowest hazard categories for each of the normative frameworks. For NEN, design criteria for LH can be used, but only up to a maximum of 45 meters between the lowest and highest sprinkler in the building. Above 45 meters, design criteria for OH3 must be used instead as per Appendix E, Section E.2.1 of NEN-EN12845. Should design criteria for OH3 be applied, design criteria can be used as calculated for Scenario 4.

What should be considered is the application of LH for NEN. As stated in Section 3.1.1, for LH the maximum compartment size for LH is a maximum of 126 m^2 and all compartments must be fire resistant for a minimum of 30 minutes. This means that additional measures must be taken at increased cost to comply with this requirement. Per the Dutch building code (Rijksoverheid, 2024) Section 4.51 paragraph 5, one compartment may only cover one dwelling, and each compartment must be at least fire resistant for a minimum of 60 minutes per Section 4.53 paragraph 1. Often apartments will not exceed 126 m^2 in floor area, thus LH for NEN can be applied considering the fire resistance requirements must already exceed those set by NEN.

However, should apartments larger than 126 m^2 be present, it is also possible to instead apply design criteria of OH1. The maximum compartment sizes do not apply to this hazard classification and thus no changes need be made for this application. If OH1 is used to design the system, use Scenario 2 to determine the design criteria.

Table 13: Design criteria for Scenario 1: Residential

Criteria	NEN	NFPA	FM Global
Hazard Classification	Up to 45m: LH Above 45m: OH3	LH	HC-1
System type	Wet	Wet	Wet
Spray density	LH: 2,5 mm/min OH3: 5 mm/min	4,1 mm/min	4 mm/min
Demand area	LH: 84 m^2 OH3: 216 m^2	140 m^2	140 m^2
Sprinkler duration	LH: 30 minutes OH3: 60 minutes	30 minutes	60 minutes
Nominal K-factor	LH: K57 OH3: K80	K80	K80
Maximum section area	LH: 10.000 m^2 OH3: 12.000 m^2 Max. 45m height difference	4830 m^2 per floor	No limit
Linear spacing	LH: 2.0 m – 4.6 m OH3: 2.0 m – 4.0 m	2.0 m – 4.6 m	2.1 m – 4.6 m
Area spacing	LH: 21 m^2 OH3: 12 m^2	20 m^2	6.0 m^2 – 20.9 m^2
Minimum pressure	LH: 0.7 bar OH3: 0.35 bar	0,5 bar	0,5 bar

Scenario 2: Offices

The second scenario covers the office spaces that are present on the upper floors (Table 14). For NFPA and FM Global the design criteria are the same as for Scenario 1, however for NEN OH1 is used instead. It is allowed to use LH for NEN in offices however, due to the prevalence of open office floor plans it would be quite difficult to maintain the maximum compartment sizes. This would lead to creating more compartments than necessary for this occupancy and higher costs of construction. It is therefore strongly advised to refrain from applying LH for NEN in office occupancies. This scenario also applies to residential occupancies where it is chosen to use OH1 instead of LH for NEN. When using OH3 for NEN design criteria calculated for Scenario 4 can be used instead

Table 14: Design criteria for Scenario 2: Offices

Criteria	NEN	NFPA	FM Global
Hazard Classification	Up to 45m: OH1 Above 45m: OH3	LH	HC-1
System type	Wet	Wet	Wet
Spray density	5 mm/min	4,1 mm/min	4 mm/min
Demand area	OH1: 72 m^2 OH3: 216 m^2	140 m^2	140 m^2
Sprinkler duration	60 minutes	30 minutes	60 minutes
Nominal K-factor	K80	K80	K80
Maximum section area	12.000 m^2	4830 m^2 per floor	No limit
Linear spacing	2.0 m – 4.0 m	2.0 m – 4.6 m	2.1 m – 4.6 m
Area spacing	12 m^2	20 m^2	6.0 m^2 – 20.9 m^2
Minimum pressure	0.35 bar	0,5 bar	0,5 bar

Scenario 3: Underground parking garage

High-rise buildings often include parking structures underneath the main structure. This is often left unheated and must thus be protected using a dry pipe sprinkler system. Design criteria for this occupancy vary in terms of stringency depending on the framework used. FM Global clearly demands the most stringent criteria, where NEN is decidedly less stringent. For this scenario the water delivery times must also be calculated as pipes are initially filled with an inert gas. For NEN OH3 must be used instead of OH2 when the height difference between lowest and highest sprinkler exceeds 45 meters. This is also calculated for this scenario. Below is an overview of the design criteria (Table 15).

Table 15: Design criteria for Scenario 3: Underground parking garage

Criteria	NEN	NFPA	FM Global
Hazard Classification	Up to 45m: OH2 Above 45m: OH3	OH2	HC-3
System type	Dry pipe	Dry pipe	Dry pipe
Spray density	5 mm/min	8,1 mm/min	12 mm/min
Demand area	OH2: 180 m^2 OH3: 270 m^2	182 m^2	330 m^2
Water delivery time	60 seconds on most remote sprinkler	50 seconds on 2 most remote sprinklers	60 seconds on single most remote sprinkler
Pipe pitch	Branch lines: 4 mm/m. Other pipes: 2 mm/m		
Sprinkler duration	60 minutes	60 minutes	60 minutes
Nominal K-factor	K80	K80	K80
Maximum section area	12.000 m^2	4830 m^2 per floor	No limit
Linear spacing	2.0 m – 4.0 m	2.0 m – 4.6 m	2.1 m – 3.7 m
Area spacing	12 m^2	12 m^2	6.0 m^2 – 9.3 m^2
Minimum pressure	0.35 bar	0,5 bar	0,5 bar

Scenario 4: Grocery store

On the ground floor of the buildings a mercantile area can often be found. This consists of one or more shops with retail items on display that are stacked as high as can be reached without equipment. One of such mercantile areas is a grocery store. Stringency per framework for this occupancy are quite closely aligned with FM Global being the most stringent of the three because of a higher demand area requirement. Below is an overview of the design criteria for this occupancy (Table 16).

Table 16: Design criteria for Scenario 4: Grocery store

Criteria	NEN	NFPA	FM Global
Hazard Classification	OH3	OH2	HC-2
System type	Wet	Wet	Wet
Spray density	5 mm/min	8,1 mm/min	8 mm/min
Demand area	216 m^2	140 m^2	230 m^2
Sprinkler duration	60 minutes	60 minutes	60 minutes
Nominal K-factor	K80	K80	K80
Maximum section area	12.000 m^2	4830 m^2 per floor	No limit
Linear spacing	2.0 m – 4.0 m	2.0 m – 4.6 m	2.1 m – 4.6 m
Area spacing	12 m^2	12 m^2	6.0 m^2 – 12.1 m^2
Minimum pressure	0.35 bar	0,5 bar	0,5 bar

Scenario 5: Bakeries

Within the same shopping centre may also be a bakery. For NEN and NFPA this occupancy is of a lower hazard classification. FM Global uses the same hazard classification for this occupancy and is also the most stringent of the three frameworks. When using OH3 for NEN design criteria calculated for Scenario 4 can be used instead. Below is an overview of all design criteria for this scenario (Table 17).

Table 17: Design criteria for Scenario 5: Bakery

Requirement	NEN	NFPA	FM Global
Hazard Classification	Up to 45m: OH2 Above 45m: OH3	OH1	HC-2
System type	Wet	Wet	Wet
Spray density	5 mm/min	6,1 mm/min	8 mm/min
Demand area	OH2: 144 m^2 OH3: 216 m^2	140 m^2	230 m^2
Sprinkler duration	60 minutes	60 minutes	60 minutes
Nominal K-factor	K80	K80	K80
Maximum section area	12.000 m^2	4830 m^2 per floor	No limit
Linear spacing	2.0 m – 4.0 m	2.0 m – 4.6 m	2.1 m – 4.6 m
Area spacing	12 m^2	12 m^2	6.0 m^2 – 12.1 m^2
Minimum pressure	0.35 bar	0,5 bar	0,5 bar

Scenario 6: Cinema theatre

Lastly, the ground floor including the first few floors may also be used for a cinema or theatre. This scenario is specifically chosen to show the differences between the normative frameworks. NEN and FM Global are similarly stringent where NEN requires a lower spray density but over a larger area and FM Global requires the inverse. However, NFPA requires a notably less stringent hazard classification. NFPA instead requires LH with a smaller spray density and much smaller demand area requirement. An overview of the criteria for this scenario is shown below (Table 18).

Table 18: Design criteria for Scenario 6: Cinema theatre

Requirement	NEN	NFPA	FM Global
Hazard Classification	OH4	LH	HC-2
System type	Wet	Wet	Wet
Spray density	5 mm/min	4,1 mm/min	8 mm/min
Demand area	360 m^2	140 m^2	230 m^2
Sprinkler duration	60 minutes	60 minutes	60 minutes
Nominal K-factor	K80	K80	K80
Maximum section area	12.000 m^2	4830 m^2 per floor	No limit
Linear spacing	2.0 m – 4.0 m	2.0 m – 4.6 m	2.1 m – 4.6 m
Area spacing	12 m^2	20 m^2	6.0 m^2 – 12.1 m^2
Minimum pressure	0.35 bar	0,5 bar	0,5 bar

5.3 Test scenario discussion and further use

Using the test scenarios, the detailed designs can be made. The detailed designs will be made upon the basic design of the mock building using the design criteria for each normative framework per scenario. The detailed designs will include:

- A basic layout of the floor,
- Placement of sprinkler heads based on the linear and area spacing criteria,
- Placement of sprinkler pipes and the initial pipe diameters, and
- The demand areas that must be calculated per normative framework.

The detailed designs can then be recreated within SprinkCALC to create a 3D-model of the system. From this model, the hydraulic analysis can be performed. During hydraulic analysis, the technical requirements can be calculated. This consists of the minimum required height difference between the water tank and sprinklers is, as well as the pipe diameters and the pressure and flow through the sprinkler heads. From the results, the design guidelines per normative can be written.

Alongside calculating the technical requirements, the scenarios also allow comparison of the stringency of the frameworks. Preliminarily, it can be seen that with the exception of Scenario 1 and 2, that the design criteria of FM Global are more stringent than NEN and NFPA. This is especially true for Scenario 3, where the spray density for FM Global is more than twice as high as that of NEN and the demand area more than twice as high as that of NFPA. For Scenario 1 and 2 however, NFPA and FM Global are equally stringent, with NEN being the least stringent. For the other scenarios, NEN and NFPA are roughly equally stringent. For Scenario 6 however, NFPA is notably less stringent than the other frameworks. Given that NEN requires a minimum hazard classification of OH3 in high-rise buildings, it can be concluded that NFPA is the least stringent normative framework to use for designing gravity-feed systems. This is in concurrence with the findings of Chapter 3 and will be further validated by the results of the hydraulic analysis.

6 System dimensioning and hydraulic analysis

With the use of the scenario design criteria, it is possible to create the detailed designs which will be used to perform the hydraulic analysis and determine pipe diameters for the system. The detailed designs are created on the basic floor plan as outlined in Subsection 5.1.1. The detailed designs are then recreated within SprinkCALC so that hydraulic analysis can be performed. The technical requirements will then be calculated with the help of hydraulic analysis. This includes the minimum required height difference between the water tank and sprinklers, as well as the pipe diameters for all piping in the system. Lastly, the pressure and flow through the sprinkler heads are also calculated. Based on the results, design guidelines can be written for each normative framework.

This chapter delves into the process and results of the hydraulic analysis performed for each of the test scenarios. Firstly, the detailed design of the sprinkler system for each of the test scenarios is shown including the initial pipe diameters (Section 6.1). Secondly, the result of the hydraulic analysis is discussed (Section 6.2). Afterwards, an overview is given of the recommended sprinkler system design including pipe diameters for each framework (Section 6.3). Lastly, the results of the hydraulic analysis and design guidelines will be discussed (Section 6.4). It is part of Phase III and IV and aims to answer Sub-Questions 3 and 4.

6.1 Detailed system designs per scenario

As stated previously, using the basic floor plan a detailed design was made for each test scenario. This includes an example layout of rooms and hallways specific to the given scenario. This layout serves only to give a basic overview of how a high-rise building may be designed but has been specifically designed to not exert influence over the results of the hydraulic calculations. Rather, the design of the sprinkler system has been made such that the sprinkler heads and pipes fit neatly between the gridlines. This allows for easy division of the floor space to suit specific needs or changes to occupation after the building is constructed.

Sprinklers are spaced based on the maximum linear and area spacing allowed by the hazard classification specific to the scenario. However, often dimensions of rooms and possible obstructions to the sprinklers make it impossible to reach the maximum allowable area spacing. To accommodate for this, a baseline reduction of 25% has been applied to the maximum area spacing of the sprinklers. This means that for scenarios where a maximum area spacing of 20m^2 is allowed, a maximum spacing of 15m^2 is used instead. For the purposes of this research, it is assumed that this reduction is sufficient to create an accurate representation of a sprinkler system with the corresponding system demand for most high-rise buildings.

The system of each scenario is connected to the same pipes leading from the water tank to the sprinkler floor. Figure 6 shows the water tank and alarm valve assembly. The riser leads down to the floor below the water tank. There the alarm valves are placed. From the alarm valves riser then leads down to the sprinkler floor. In Figure 7 the riser arrives at the sprinkler floor. Here is connects to the floor control assembly, which consists of a floor control valve and a check valve. Finally, from the floor control assembly, the water flows through the feed main to the sprinkler zone.

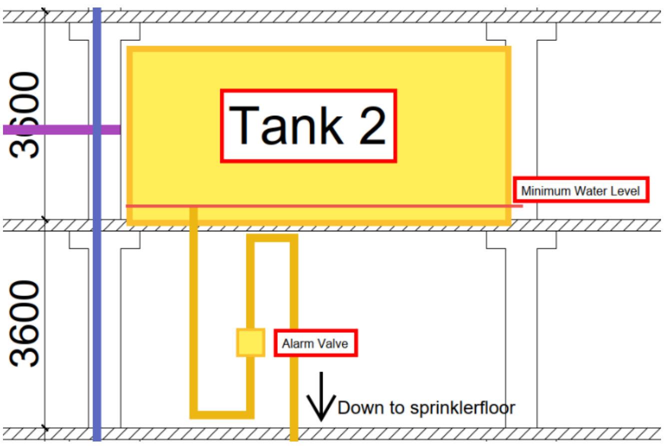

Figure 6: Water tank and alarm valve setup

The sprinkler zone is the size of the demand area as specified in the design criteria per scenario. The demand area is the area in which the sprinklers will activate in case of fire. For hydraulic analysis it is required by all three normative frameworks that the demand area is placed at the hydraulically most unfavourable area. This is the area at which the demand on the water supply system is the largest. Often this is the area furthest away from the system riser. This is because it must be validated that the system can supply the requisite pressure and flow at any point in the system.

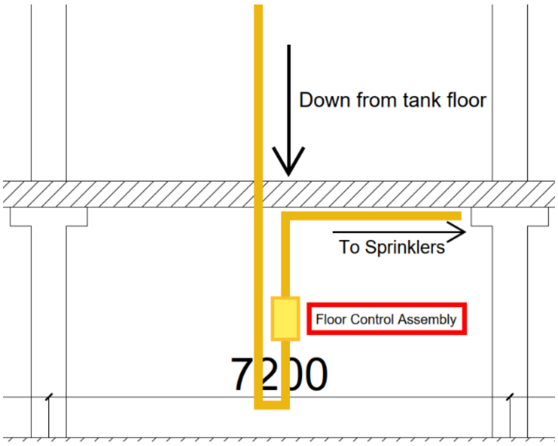

Figure 7: Floor control valve assembly

Furthermore, only NEN also requires that the demand area is calculated the hydraulic most favourable area. This is the inverse of the most unfavourable area and must be placed such that the demand on the water supply systems is the lowest. The lower demand on the system increases the pressure on the sprinkler heads and thus increases the system water consumption. NEN requires that the water tank is sized to the greater system water consumption of the most favourable area.

For each scenario the unfavourable area for the NEN system shall be shown. System designs for all three frameworks in greater detail can instead be found in Appendix A3. The detailed design drawings contain:

- Walls and doors in the colour indigo,
- Furniture, floor markings, and other non-structural elements in brown,
- The initial pipe diameters calculated for the system are shown next to the pipes,
- Distance between sprinklers and other components are shown with red lines and the distance in meters rounded to a tenth,
- Sprinkler components for NEN in green,
- Sprinkler components for NFPA in red, and
- Sprinkler components for FM Global in light blue.

Scenario 1: Residential detailed design layout

Scenario 1 is based on protecting the residential dwellings that are often present within high-rise buildings. This scenario covers the LH hazard classification for NEN and NFPA and HC-1 for FM Global. The limitation of 126m^2 per dwelling as per NEN has been taken into account. The unfavourable area is found in the bottom left part of the floor as this is the furthest away from the system riser in the shaft. The apartment has an entrance with a bedroom to the right, a bathroom below, and a living area/kitchen to the left. For all frameworks the maximum area spacing for sprinklers is 20m^2. Therefore, to neatly fit the sprinkler components a linear spacing of 3,6 meters by 3,6 meters has been used. This means that each individual sprinkler protects 12,96m^2.

The most favourable area, visible on the detailed design in Appendix A3.1, has been placed in the apartment just above the shaft. This is because the hallway exceeds the 126m^2 limit and must thus be protected according to hazard classification OH1 for NEN. This means that the favourable area cannot be placed there. Thus, the closest LH classified room on this floor is just above the shaft room.

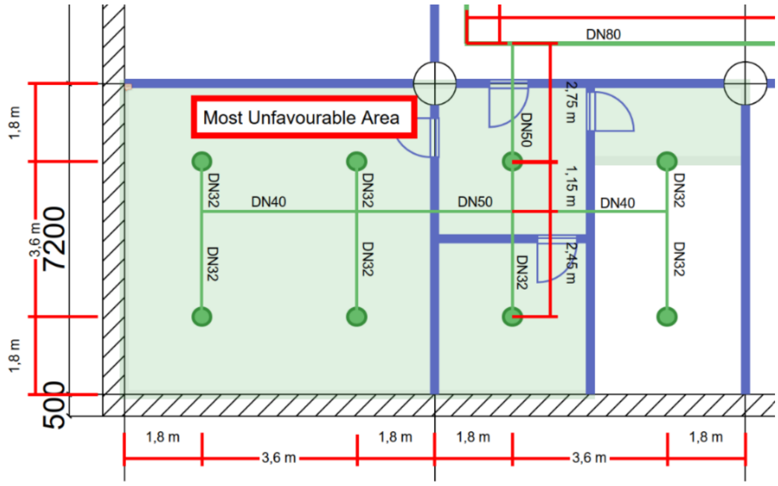

Figure 8: Scenario 1: Residential partial drawing of the system design for NEN (Detailed drawing can be found in Appendix A3.1)

Scenario 2: Offices detailed design layout

This scenario covers offices that often take up the higher floors of a high-rise building. This covers the hazard classifications OH1 for NEN, LH for NFPA, and HC-1 for FM Global. Like Scenario 1, the most unfavourable area has been placed in the bottom left corner of the floor. The favourable area is this time placed in the hallway outside the shaft and slightly into the office on the right. The office represents a smaller, open-office floor plan with two smaller meeting rooms. The brown divider walls serve to divide the office into several desk clusters with some cabinets for file storage along the divider walls, not drawn in this design. NFPA and FM Global specify a maximum area spacing of 20m², thus the same linear spacing is used as in scenario 1. However, OH1 for NEN specifies 12m² However, OH1 for NEN specifies 12m² as such a linear spacing of 2,4 meters by 3,6 meters is used for NEN. This results in an area spacing of 8,64m². The detailed design can be found in Appendix A3.2.

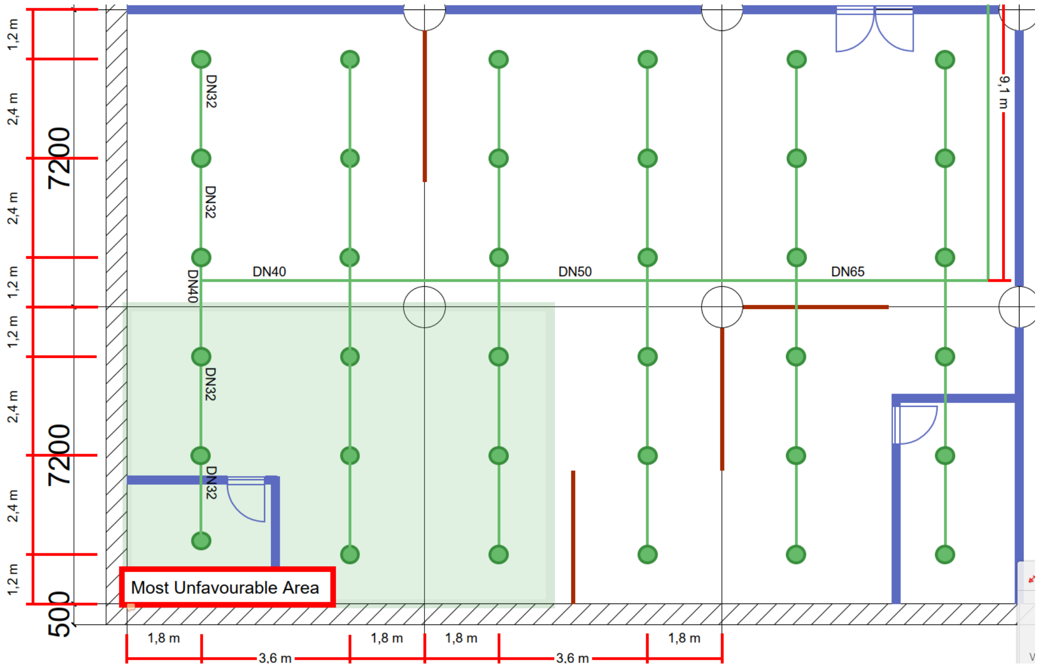

Figure 9: Scenario 2: Offices partial drawing of the system design for NEN (Detailing drawing can be found in Appendix A3.2)

Scenario 3: Underground parking garage detailed design layout

The scenario describes the underground parking garage beneath the structure. This covers hazard classifications OH2 for NFPA, HC-3 for FM Global, and for NEN both OH2 and OH3 are covered. The unfavourable area is located at the left side of the garage. The favourable area instead is placed on right outside the central lift and staircase room visible in the detail drawing in Appendix A3.3. NEN and NFPA both specify a maximum area spacing of 12m² for which a linear spacing of 2,4 meters by 3,6 meters is used. FM Global uses 9m² for which a linear spacing of 2,4 meters by 2,8 meters. This results in an area spacing of 8,64m² and 6,72m² respectively. As there is a risk of frost in a parking garage, a dry pipe system is used for this scenario. This means that additionally the pipes must be pitched to ensure any unwanted water in the system when not in operation flows back to a drain point. Branch lines are pitched 4 mm/m whereas other pipes are pitched 2 mm/m.

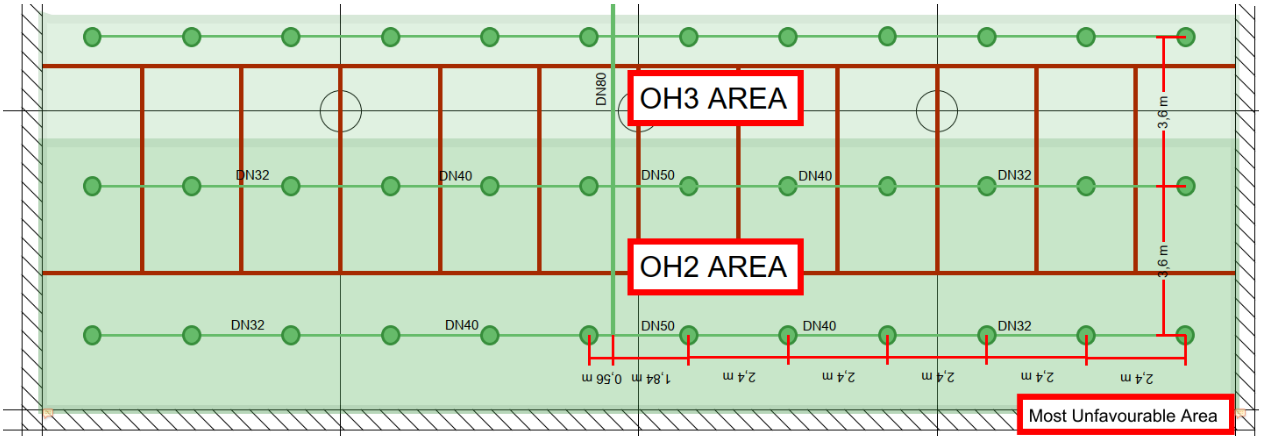

Figure 10: Scenario 3: Underground parking garage partial drawing of the system design of the unfavourable area for NEN (Detailed drawing can be found in Appendix A3.3)

Scenario 4: Grocery store and Scenario 5: Bakery detailed design layout

Scenario 4 and 5 have been drawn together as part of the ground floor of the high-rise building. Scenario 4 covers hazard classes OH3 for NEN, OH2 for NFPA, and HC-2 for FM Global. Scenario 5 covers OH2 for NEN, OH1 for NFPA, and HC-2 as well for FM Global. Both scenarios specify the same maximum area spacing of 12m^2 for all frameworks. Thus, for this a linear spacing of 2,4 meters by 3,6 meters is used, resulting in an area spacing of 8,64m^2 per sprinkler. The favourable and unfavourable areas of both scenarios fall within the same room, as other spaces on the ground floor may have lighter or heavier hazard classifications and are thus not part of the same hydraulic analysis. The detailed design of Scenario 4 and five can be found in Appendix A3.4.

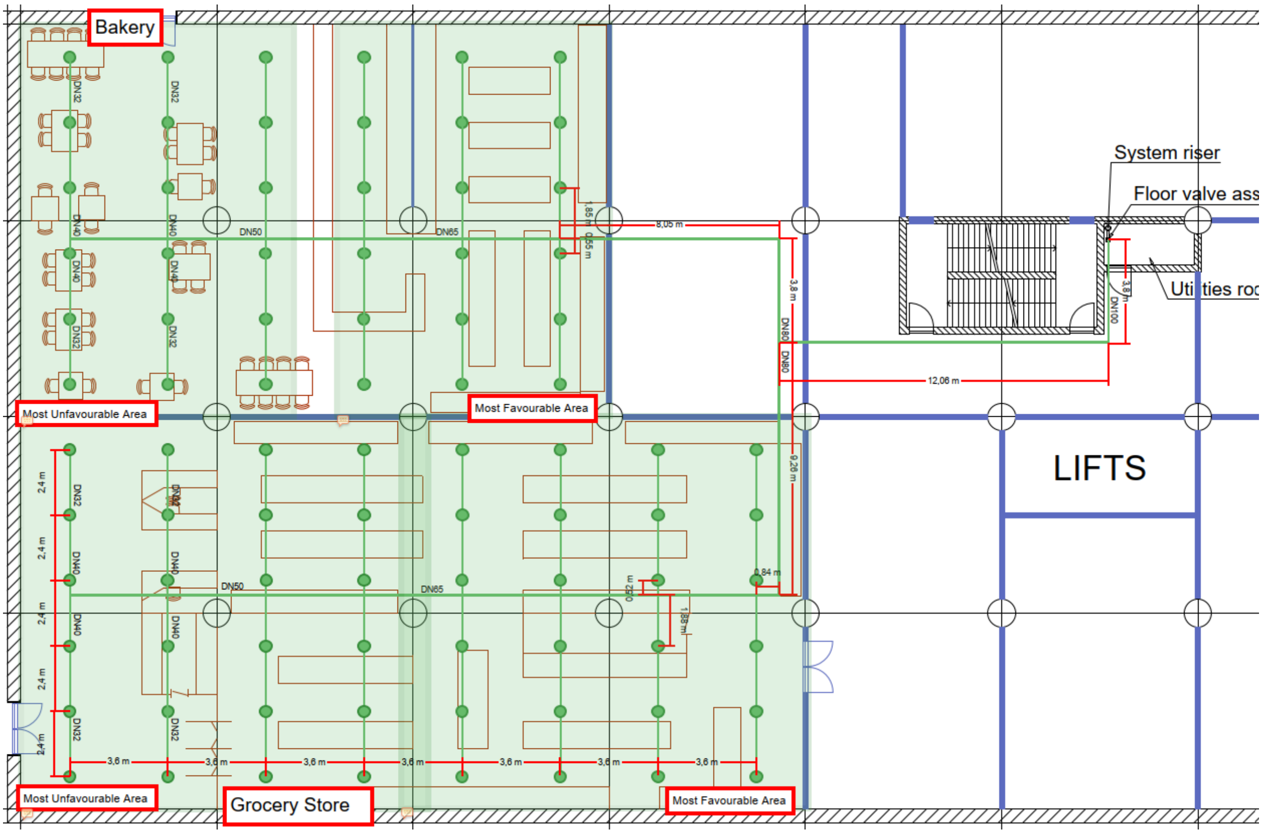

Figure 11: Scenario 4: Grocery store and Scenario 5: Bakery partial drawing of the system designs for NEN (Detailing drawing can be found in Appendix A3.4)

Scenario 6: Cinema theatre detailed design drawings

Scenario 6 describes the presence of a cinema theatre on the ground floor of the high-rise. This scenario covers hazard classifications OH4 for NEN, LH for NFPA, and HC-2 for FM Global. It was found that the unfavourable area for this scenario is on the right side of the hallway connecting the theatre halls. The favourable is on the left side instead. NEN and FM Global both use a maximum area spacing of 12m² for which a linear spacing of 2,4 meters by 3,6 meters is used. NFPA specifies a maximum area spacing of 20m² for which a linear spacing of 3,6 meters by 3,6 meters was used. This results in an area spacing of 8,64m² and 12,96m² respectively. The detailed design can be found in Appendix A3.5.

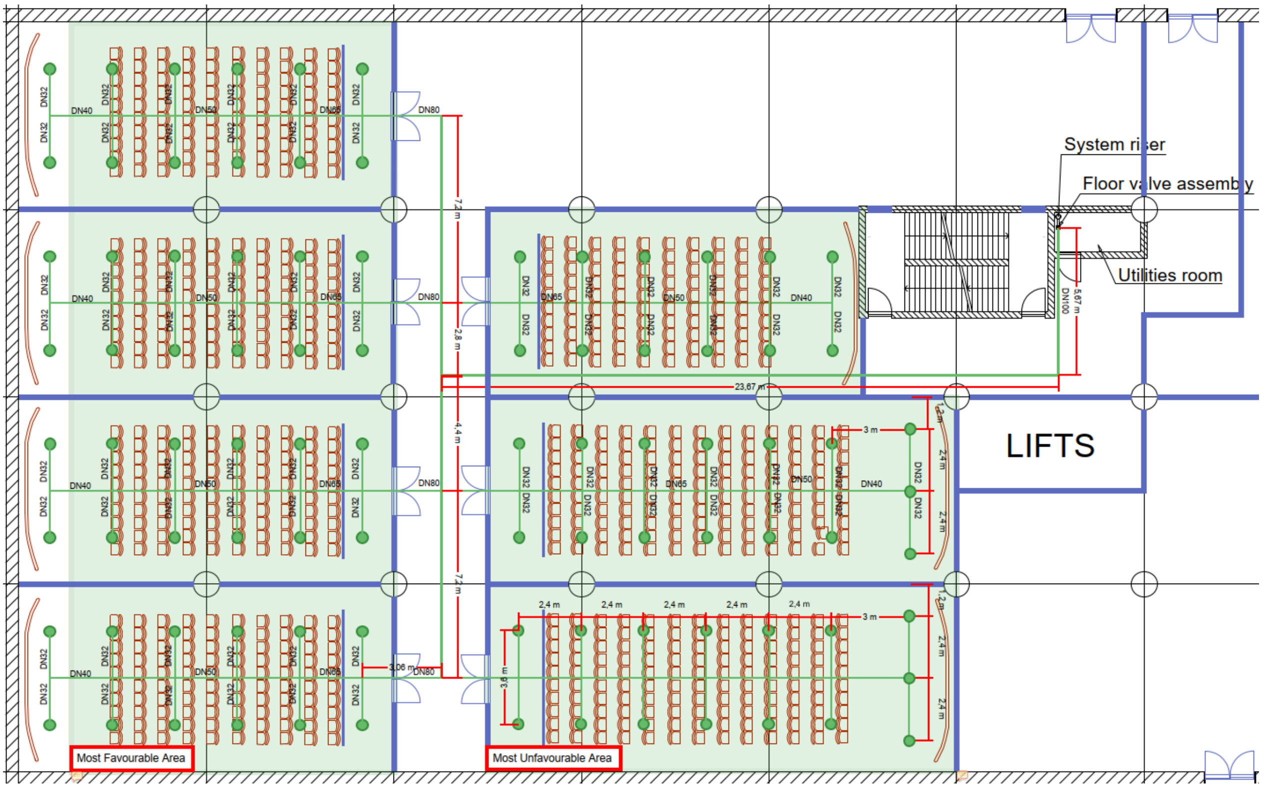

Figure 12: Scenario 6: Cinema theatre partial drawing of the system design for NEN (Detailed drawing can be found in Appendix A3.5)

6.2 Hydraulic analysis of the systems

With the use of the detailed designs, it is possible to perform the hydraulic analyses for all scenarios to determine the technical requirements of the system. These include the minimum height difference between the sprinklers and water tank, as well as the recommended pipe diameters, and pressure and flow through the sprinkler heads. This is done by recreating the design within SprinkCALC to create a digital 3D-model of the system. The software can then calculate the technical requirements based on the model.

This chapter details the process of performing hydraulic analysis and the results from it. Firstly, the steps taken during hydraulic analysis are described (Subsection 6.2.1). Afterwards, the results from the hydraulic analysis are compared between normative frameworks (Subsection 6.2.2). Based on the results of this section, the design guidelines for each normative framework can be written.

6.2.1 Performing hydraulic analysis

Using standardized hydraulic formulas, SprinkCALC can perform the required calculated to determine the technical requirements to operate the sprinkler system. This is done by calculating the flow and pressure losses or gains through each pipe in the system. These calculations can be done in two different methods. These are:

- **Demand mode**

In this mode, the demand of the system is calculated. This is done to determine the minimum required pressure and flow that the water supply system must deliver to operate the sprinklers. In this research this mode is used to determine the minimum height difference between the water tank and sprinklers.

- **Supply mode**

This mode calculates the pressure and flow through the sprinkler head with the water supply system operating at maximum capacity. This is usually done by filling in the supply curve, which shows the pressure the pump can deliver at specific flow rates. However, since a gravity-feed system operates without a pump, a linear supply curve has been filled with zero pressure. This mode is used to calculate the size of the water tank, as the water supply system always operates at maximum capacity and may thus exceed the system demand. This increases the system consumption and thus a larger water tank is required.

For the underground parking garage, the water delivery times were also calculated. This time can be split into two parts. The first is the trip-time, or the time it takes for the dry pipe valve to open after a sprinkler head opens. The second is the travel time, or the time it takes for the water to travel between the dry pipe valve to the sprinkler heads and until operating pressure is reached. The trip-time can be improved in the same ways as can be done with a traditional pumped system. Thus, for the purposes of this research only the travel-time is considered. For all frameworks, the travel time was between 18-25 seconds. This falls quite comfortably within the limits for water delivery time, with enough time remaining for the trip-time.

As the height difference increases, the pressure on the system increases. This influences both static and dynamic pressures of the system. The static pressure is the pressure within the system when it is not in use. The static pressure increases with 0,98 bar per ten meters of height. As all frameworks state that the maximum pressure within standard sprinkler system components may not exceed 12 bar, this means that the maximum height difference between the sprinklers and water tank is roughly 120 meters. When going above 120 meters, high-pressure components must be used to account for the increased pressure, at increased cost of the system. It is recommended to avoid the need to use high-pressure components whenever possible.

The dynamic pressure is the pressure within the system when it is in operation. This also increases with an increase in height difference. Because of pressure losses due to friction there is no risk of exceeding the 12-bar pressure limit if the static pressure is also below 12 bar. However, the increased dynamic pressure does influence the systems water consumption. As an increase in dynamic pressure leads to an increased pressure on the sprinkler heads. Ultimately, this also increases the amount of water discharged per minute. With the increase in system consumption, the water tank must also be enlarged to account for this change.

To reduce the effects of the dynamic pressure increase, it was chosen to reduce pipe diameters after a certain height difference. Pressure losses are greater in smaller diameter pipes. Greater pressure losses reduce the dynamic pressure and thus also the pressure on the sprinkler heads. As such, larger height differences can be covered by the same size water tank to supply the system.

6.2.2 Results of hydraulic analysis

Firstly, the minimum height necessary to pressurize the system was calculated. The results can be seen in Table 19. The first two scenarios are very similar with only 10-13 meters of height difference necessary to create the required pressure. As residences and offices often occupy the top floors of a high-rise building, it would only be necessary to protect the upper four floors with the help of a small electric pump. The rest of the floors can all be protected with the use of the gravity-feed system.

The other four scenarios require more height difference as these are the more stringent hazard classifications. However, considering these scenarios and the accompanying hazard classifications are typically only found on the first couple of floors, such a height difference can easily be created within a high-rise building.

Table 19: Calculated minimum height difference for all scenarios

Scenario	NEN	NFPA	FM Global
Residential	10m	12m	12m
Offices	13m	13m	13m
Underground parking garage	OH2: 21m OH3: 25m	33m	32m
Grocery store	23m	23m	33m
Bakery	15m	18m	32m
Cinema theatre	25m	14m	20m

Afterwards, the system consumption over height difference was calculated. This was done in 10-meter increments starting from the lowest minimum height difference. Figure 13 shows an overview of the results of these calculations for all scenarios. The colour of the line corresponds to the normative framework. The colours are:

- Dark green for the favourable area of NEN,
- Light green for the unfavourable area of NEN,
- Red for NFPA,
- Blue for FM Global,
- Light pink for the favourable area of OH3 NEN in Scenario 3, and
- Orange for the unfavourable area of OH3 NEN in Scenario 3.

The pipe diameter reduction per scenario can be observed at the point where consumption steeply drops at the same height difference. As this research aims to only provide a simple starting point for designing gravity-feed systems, this was only done once per scenario. For a real system, pipe diameters can be constricted multiple times in a system to create an even more gradual increase in system consumption.

By reducing the pipe diameters, it is possible to limit the system consumption increase to one-and-a-half times the minimum system consumption for lighter hazard classifications and two times the minimum system consumption for heavier hazard classifications.

For Scenario 1 and 2 the curves for NFPA and FM Global overlap. This is because the density and demand area for both frameworks are nearly identical. The other scenarios however, FM Global has a much-increased system consumption than NEN and NFPA. This is because FM Global has more stringent requirements for sprinkler systems. This is especially true for Scenario 3, where the system consumption for FM Global is nearly twice as high as compared to NEN and NFPA. Thus, it is recommended to not use FM Global unless enforced by the AHJ or the insurance provider.

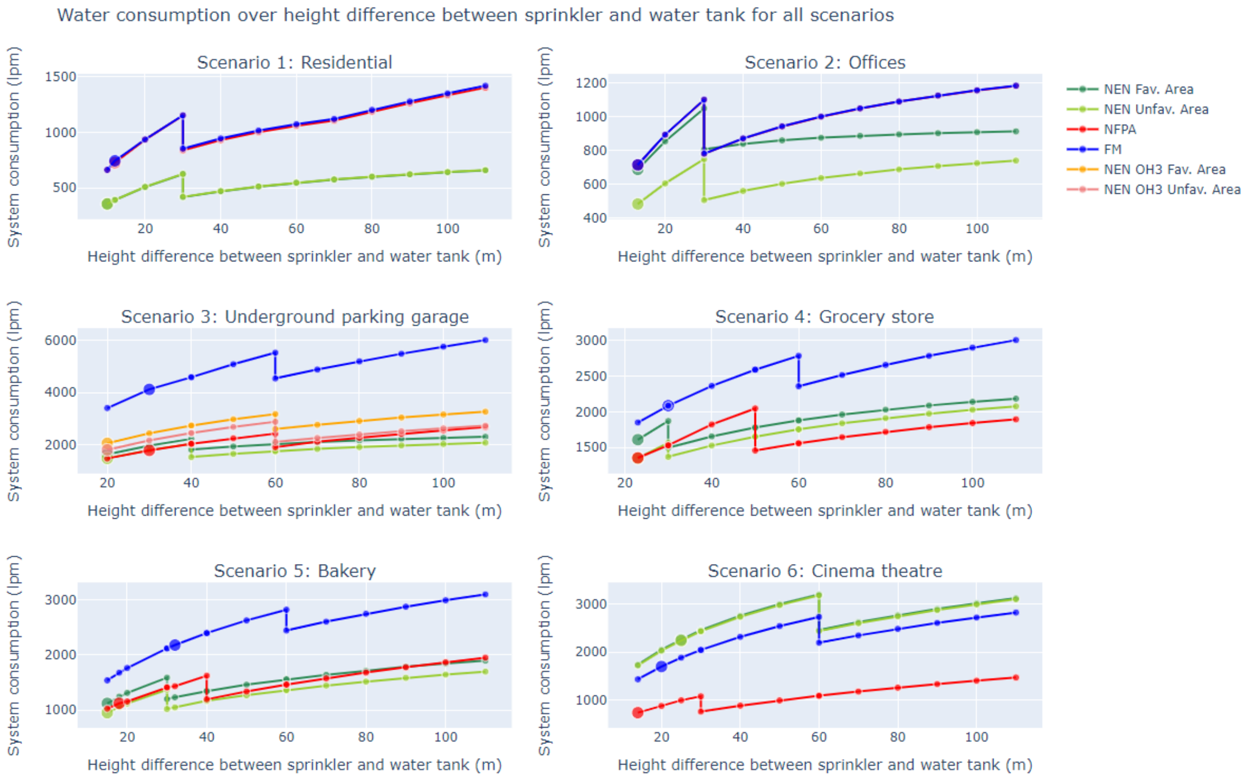

Figure 13: Hydraulic analysis results for all scenarios with system consumption over height difference

6.3 System design guidelines per framework

With the pipe diameters used during hydraulic analysis, design guidelines for designing gravity-feed systems can be made. Every building poses different design challenges that must be considered for a sprinkler system. It is not possible to provide a guideline that fits all situations. Instead, the guidelines serve to provide a starting point for gravity-feed system dimensioning and show the considerations taken when designing such a system compared to a traditional pumped system. Once the basic design of the system has been made, it must still be substantiated using hydraulic analysis.

It is recommended to use a minimum of two water tanks in a high-rise building. The first tank is placed on the lower floors, at the ideal height to serve the heavier hazard classifications typically found on the lower floors of the building. The heavier hazard classifications require larger water tanks due to the higher system consumption. Thus, placing the tank higher than necessary above the sprinkler zone results in greater increases in tank size compared to the much smaller water tanks necessary for protecting the lighter hazard classifications on the top floors. The second water tank should be placed on the top floor and protects the light hazard classes up until the first tank reaches the minimum height difference necessary.

For each framework a table is created showing the recommended minimum height difference and the initial pipe diameters for branch lines, cross mains, feed mains, and the riser. Secondly, it shows the height difference at which to constrict the pipe diameters and to which diameters to constrict the pipes to. The pipe diameters within the design guideline tables are the same as the pipe diameters used during hydraulic analysis. Some sizes have been interpolated from the sizes before and after it. This is because some designs for the test scenarios did not contain a cross main which connected to 6 sprinklers or less for example. As these design guidelines serve only as a starting point for designing gravity-feed systems, the pipe diameters will still be validated per sprinkler system with the use of hydraulic analysis.

6.3.1 Design guidelines for NEN

For NEN all the hazard classifications are included in the design guidelines. However, when the difference between the lowest and highest sprinkler within a building exceeds 45 meters, all hazard classifications must be upgraded to a minimum of OH3. Below in Table 20 is the system design guideline for NEN.

Table 20: Design guideline for gravity-feed systems using NEN

<table>
<tr><th colspan="2">Initial pipe diameters</th><th>LH</th><th>OH1</th><th>OH2</th><th>OH2 dry</th><th>OH3</th><th>OH3 dry</th><th>OH4</th></tr>
<tr><td colspan="2">Recommended min. height difference</td><td>15m</td><td>15m</td><td>20m</td><td>25m</td><td>25m</td><td>30m</td><td>30m</td></tr>
<tr><td rowspan="3">Branch line</td><td>Connected to 2 sprinklers</td><td rowspan="3">DN32</td><td>DN32</td><td>DN32</td><td>DN32</td><td>DN32</td><td>DN32</td><td>DN32</td></tr>
<tr><td>Connected to 4 sprinklers</td><td>DN40</td><td>DN40</td><td>DN40</td><td>DN40</td><td>DN40</td><td>DN40</td></tr>
<tr><td>Connected to more</td><td>DN50</td><td>DN50</td><td>DN50</td><td>DN50</td><td>DN50</td><td>DN50</td></tr>
<tr><td rowspan="5">Cross main</td><td>Connected to 2 sprinklers</td><td>DN40</td><td>DN40</td><td>DN40</td><td>D40</td><td>DN40</td><td>DN40</td><td>DN40</td></tr>
<tr><td>Connected to 6 sprinklers</td><td rowspan="4">DN50</td><td>DN50</td><td rowspan="2">DN50</td><td rowspan="3">DN80</td><td rowspan="2">DN50</td><td rowspan="3">DN80</td><td>DN50</td></tr>
<tr><td>Connected to 12 sprinklers</td><td rowspan="2">DN65</td><td>DN65</td></tr>
<tr><td>Connected to 18 sprinklers</td><td>DN65</td><td>DN65</td><td rowspan="2">DN80</td></tr>
<tr><td>Connected to more</td><td>DN80</td><td>DN80</td><td>DN100</td><td>DN80</td><td>DN100</td></tr>
<tr><td colspan="2">Feed main</td><td>DN80</td><td>DN80</td><td>DN100</td><td>DN100</td><td>DN100</td><td>DN100</td><td>DN100</td></tr>
<tr><td colspan="2">Riser</td><td>DN100</td><td>DN100</td><td>DN100</td><td>DN100</td><td>DN100</td><td>DN100</td><td>DN100</td></tr>
<tr><th colspan="2">Reduce pipe diameters below</th><th>30m</th><th>30m</th><th>30m</th><th>40m</th><th>30m</th><th>60m</th><th>60m</th></tr>
<tr><td rowspan="3">Branch line</td><td>Connected to 2 sprinklers</td><td rowspan="3">DN25</td><td>DN25</td><td>DN25</td><td>DN32</td><td>DN25</td><td>DN32</td><td>DN32</td></tr>
<tr><td>Connected to 4 sprinklers</td><td rowspan="2">DN32</td><td rowspan="2">DN32</td><td rowspan="2">DN40</td><td rowspan="2">DN32</td><td rowspan="2">DN40</td><td>DN40</td></tr>
<tr><td>Connected to more</td><td>DN50</td></tr>
<tr><td rowspan="5">Cross main</td><td>Connected to 2 sprinklers</td><td>DN32</td><td>DN32</td><td>DN32</td><td>DN40</td><td>DN40</td><td>DN40</td><td>DN40</td></tr>
<tr><td>Connected to 6 sprinklers</td><td rowspan="4">DN40</td><td>DN40</td><td>DN40</td><td rowspan="4">DN80</td><td rowspan="3">DN65</td><td rowspan="4">DN80</td><td>DN50</td></tr>
<tr><td>Connected 12 sprinklers</td><td rowspan="3">DN50</td><td rowspan="2">DN50</td><td>DN65</td></tr>
<tr><td>Connected to 18 sprinklers</td><td rowspan="2">DN80</td></tr>
<tr><td>Connected to more</td><td>DN65</td><td>DN80</td></tr>
<tr><td colspan="2">Feed main</td><td>DN50</td><td>DN50</td><td>DN80</td><td>DN80</td><td>DN80</td><td>DN80</td><td>DN80</td></tr>
<tr><td colspan="2">Riser</td><td>DN50</td><td>DN50</td><td>DN80</td><td>DN80</td><td>DN80</td><td>DN100</td><td>DN100</td></tr>
</table>

6.3.2 Design guidelines for NFPA

For high-rise buildings water tanks must, at minimum, be compartmentalized into two sections each containing 50% of the system demand. This must be done for all water tanks present within a building. Below in Table 21 is the system design guideline for gravity-feed systems using NFPA.

Table 21: Design guideline for gravity-feed systems using NFPA

<table>
<tr><th colspan="2">Initial pipe diameters</th><th>LH</th><th>OH1</th><th>OH2</th><th>OH2 dry</th></tr>
<tr><td colspan="2">Recommended min. height difference</td><td>15m</td><td>25m</td><td>25m</td><td>35m</td></tr>
<tr><td rowspan="3">Branch line</td><td>Connected to 2 sprinklers</td><td>DN32</td><td>DN32</td><td>DN32</td><td>DN32</td></tr>
<tr><td>Connected to 4 sprinklers</td><td rowspan="2">DN40</td><td rowspan="2">DN40</td><td rowspan="2">DN40</td><td>DN40</td></tr>
<tr><td>Connected to more</td><td>DN50</td></tr>
<tr><td rowspan="5">Cross main</td><td>Connected to 2 sprinklers</td><td>DN40</td><td>DN40</td><td>DN40</td><td>DN40</td></tr>
<tr><td>Connected to 6 sprinklers</td><td>DN50</td><td rowspan="2">DN50</td><td rowspan="2">DN65</td><td rowspan="3">DN80</td></tr>
<tr><td>Connected to 12 sprinklers</td><td rowspan="2">DN65</td></tr>
<tr><td>Connected to 18 sprinklers</td><td>DN65</td><td rowspan="2">DN80</td></tr>
<tr><td>Connected to more</td><td>DN80</td><td>DN80</td><td>DN100</td></tr>
<tr><td colspan="2">Feed main</td><td>DN80</td><td>DN100</td><td>DN100</td><td>DN100</td></tr>
<tr><td colspan="2">Riser</td><td>DN100</td><td>DN100</td><td>DN100</td><td>DN100</td></tr>
<tr><th colspan="2">Reduce pipe diameters below</th><th>30m</th><th>40m</th><th>50m</th><th>60m</th></tr>
<tr><td rowspan="3">Branch line</td><td>Connected to 2 sprinklers</td><td>DN25</td><td>DN25</td><td>DN32</td><td>DN32</td></tr>
<tr><td>Connected to 4 sprinklers</td><td rowspan="2">DN32</td><td rowspan="2">DN32</td><td rowspan="2">DN40</td><td>DN40</td></tr>
<tr><td>Connected to more</td><td>DN50</td></tr>
<tr><td rowspan="5">Cross main</td><td>Connected to 2 sprinklers</td><td>DN32</td><td>DN32</td><td>DN40</td><td>DN40</td></tr>
<tr><td>Connected to 6 sprinklers</td><td>DN40</td><td rowspan="3">DN50</td><td rowspan="2">DN50</td><td rowspan="4">DN80</td></tr>
<tr><td>Connected 12 sprinklers</td><td rowspan="2">DN50</td></tr>
<tr><td>Connected to 18 sprinklers</td><td rowspan="2">DN65</td></tr>
<tr><td>Connected to more</td><td>DN65</td><td>DN65</td></tr>
<tr><td colspan="2">Feed main</td><td>DN65</td><td>DN80</td><td>DN80</td><td>DN80</td></tr>
<tr><td colspan="2">Riser</td><td>DN65</td><td>DN100</td><td>DN80</td><td>DN100</td></tr>
</table>

6.3.3 Design guidelines for FM Global

Lastly, the design guidelines for FM Global have been created. The design guidelines are shown below in Table 22.

Table 22: Design guideline for gravity-feed systems using FM Global

<table>
<tr><th colspan="2">Initial pipe diameters</th><th>HC-1</th><th>HC-2</th><th>HC-3</th><th>HC-3 dry</th></tr>
<tr><td colspan="2">Recommended min. height difference</td><td>15m</td><td>35m</td><td>40m</td><td>40m</td></tr>
<tr><td rowspan="2">Branch line</td><td>Connected to 2 sprinklers</td><td>DN32</td><td>DN32</td><td>DN32</td><td>DN32</td></tr>
<tr><td>Connected to more</td><td>DN40</td><td>DN40</td><td>DN40</td><td>DN40</td></tr>
<tr><td rowspan="5">Cross main</td><td>Connected to 2 sprinklers</td><td>DN40</td><td>DN40</td><td>DN40</td><td>DN40</td></tr>
<tr><td>Connected to 6 sprinklers</td><td>DN50</td><td rowspan="2">DN80</td><td>DN80</td><td rowspan="3">DN100</td></tr>
<tr><td>Connected to 12 sprinklers</td><td rowspan="2">DN65</td><td rowspan="3">DN100</td></tr>
<tr><td>Connected to 18 sprinklers</td><td rowspan="2">DN100</td></tr>
<tr><td>Connected to more</td><td>DN80</td><td>DN150</td></tr>
<tr><td colspan="2">Feed main</td><td>DN80</td><td>DN100</td><td>DN100</td><td>DN150</td></tr>
<tr><td colspan="2">Riser</td><td>DN100</td><td>DN100</td><td>DN150</td><td>DN150</td></tr>
<tr><th colspan="2">Reduce pipe diameters below</th><th>30m</th><th>50m</th><th>60m</th><th>60m</th></tr>
<tr><td rowspan="2">Branch line</td><td>Connected to 2 sprinklers</td><td>DN25</td><td>DN32</td><td>DN32</td><td>DN32</td></tr>
<tr><td>Connected to more</td><td>DN32</td><td>DN40</td><td>DN40</td><td>DN40</td></tr>
<tr><td rowspan="5">Cross main</td><td>Connected to 2 sprinklers</td><td>DN32</td><td>DN40</td><td>DN40</td><td>DN40</td></tr>
<tr><td>Connected to 6 sprinklers</td><td>DN40</td><td rowspan="2">DN65</td><td rowspan="2">DN80</td><td rowspan="4">DN100</td></tr>
<tr><td>Connected 12 sprinklers</td><td rowspan="2">DN50</td></tr>
<tr><td>Connected to 18 sprinklers</td><td rowspan="2">DN80</td><td rowspan="2">DN100</td></tr>
<tr><td>Connected to more</td><td>DN65</td></tr>
<tr><td colspan="2">Feed main</td><td>DN65</td><td>DN100</td><td>DN100</td><td>DN100</td></tr>
<tr><td colspan="2">Riser</td><td>DN65</td><td>DN100</td><td>DN100</td><td>DN150</td></tr>
</table>

6.4 Hydraulic analysis and design guideline discussion

The findings of this chapter clearly show the difference between the three normative frameworks. As was already concluded in previous chapters, FM Global is the most stringent normative framework. The results from the hydraulic analysis show that for most test scenarios FM Global requires a greater height difference between the water tank and sprinklers and has a higher system consumption. This is highlighted by Scenario 3 where the consumption of FM Global is nearly twice as high as both NEN and NFPA. Also in the design guidelines, FM Global often requires larger pipe diameters to function. It is therefore recommended to avoid using FM Global whenever possible. However, it may be that AHJ or insurance broker will require that FM Global be applied. In such cases, it is still possible to design a gravity-feed system using this normative framework.

The difference between NEN and NFPA is much smaller. In many cases, NEN requires a slightly lower height difference and system consumption than NFPA. The pipe diameters from the design guidelines are also smaller. However, NEN requires a minimum hazard classification of OH3 for all occupancies when the height difference between the lowest and highest sprinkler exceeds 45 meters. Therefore, considering that high-rise buildings often exceed this limit, NFPA is instead the less stringent normative framework of the two. As such, it is recommended to use NFPA to design gravity-feed systems for high-rise buildings whenever possible.

The design guidelines created in chapter have been based on the pipe diameters used during the hydraulic analysis. With the baseline reduction to sprinkler area spacing, which was applied, it is assumed these design guidelines will serve as a sufficient starting point when designing gravity-feed systems. Any systems designed using these guidelines must still be validated using hydraulic analysis. Thus, the accuracy and applicability of these guidelines can also be monitored by checking whether many adjustments needed to be made after the initial design and calculation. In such cases where many adjustments were necessary, it would be possible to continue this research to adjust the design guidelines such that the correct accuracy and applicability is restored.

7 Conclusion

This research aimed to answer the question: “What are the legislative and technical requirements for applying gravity-feed systems for operation of sprinkler systems in high-rise buildings according to NEN, NFPA, and FM Global so that design guidelines can be written?”. For this, qualitative research was done into the requirements imposed by the three normative frameworks. Furthermore, quantitative research was done into how gravity-feed sprinkler systems should be designed.

The three normative frameworks all specify that sprinkler systems must be designed based on the types of hazards it protects. These hazards are split up into hazard classifications. These hazard classifications dictate the size of the demand area where sprinklers will activate and how dense these sprinklers must spray water. Furthermore, the normative frameworks specify how the sprinkler heads must be spaced in terms of distance between heads, as well as the area that a single sprinkler head may protect. To substantiate that a sprinkler system meets these design criteria, it must be calculated that it can deliver the required density at the appropriate pressure over all sprinkler heads within the demand area.

Water tanks must be sized based on the system consumption per minute for the total sprinkler duration. Furthermore, water tanks must be equipped to be able to refill the tank within eight hours after sprinkler system activation. The normative frameworks also require that water tanks within high-rise buildings are equipped with redundancy, either in the form of compartmentalized tanks or dual system risers. Lastly, it was discovered that the structure of the building must be altered at the places where water tanks are placed. This is because large quantities of water exert greater force on the floor than they are typically designed for. Furthermore, water tanks at height in a building may also interfere with vibration dampening devices, as free flowing water can enhance vibrations within the building.

From the calculations made, all scenarios that fall within the scope of this research can be reasonably protected using a gravity-feed sprinkler system. This covers all non-storage hazard classifications that can reasonably be found within high-rise buildings. The occupancies covered in this research are: residences, offices, underground parking garages, grocery stores, bakeries, and cinema theatres.

From the hydraulic analysis it became clear that greater height differences between sprinkler and water tank resulted in greater system water consumption. This is because a greater height difference increases the dynamic pressure in the system, which increases pressure and flow in the sprinkler heads. This can however be alleviated by constricting the pipe diameters after a specific height below the water tank. This increases pressure losses due to friction and thus reduces the pressure on and flow through the sprinkler heads. The limit for the maximum height difference is the same for all systems. As the static pressure will exceed the 12-bar limit of sprinkler system components around a height difference of roughly 120 meters. The minimum height difference depends on the hazard classification but ranges between 15-33 meters. For the highest tank this means that the top floors must still be protected with a small fire pump. It was found that NFPA is the least stringent, and thus the most favourable framework to use. Inversely, FM Global was found to be much more stringent with system consumption being higher than both NEN and NFPA for most scenarios.

To conclude, it is possible to protect high-rise buildings using a gravity-feed sprinkler system with all three normative frameworks. For this, an individual water tank can supply floors up to roughly 120 meters below it, but the size must be adjusted for the increased flow on the lower floors. This size adjustment can be reduced by constricting pipe diameters a certain height below the water tank, depending on the hazard classification. With a gravity-feed system only the top few floors need to be protected with a much smaller fire pump. The rest of the building can be protected using only the gravity-feed system utilising one or more water tanks depending on the size of the building. Based on the hydraulic analysis, design guidelines have been written per normative framework which provides a starting point for designing gravity-feed systems.

8 Recommendations

When designing a gravity-feed sprinkler system within high-rise buildings it is recommended to use the design guidelines as a starting point. Using the guidelines, it is easy to quickly create a preliminary design of the system. This design must later of course be validated and possibly adjusted with the help of hydraulic analysis.

It is also recommended to use the NFPA framework. This is because NEN and FM Global impose stricter requirements. NEN requires all hazard classifications to be upgraded to a minimum of OH3 in buildings where the height difference between the lowest and highest sprinkler head exceeds 45 meters. FM Global requires larger demand areas and larger spray densities for most hazard classifications. Because of this, NEN and FM Global based sprinkler systems require larger water tanks and pipe diameters as the system consumption is higher compared to NFPA.

Furthermore, it is advised to constrict the pipe diameters after a certain height below the water tank. This height depends on the framework and hazard classification but serves to reduce the increase in dynamic pressure due to a greater height difference between sprinkler and water tank. This reduces the pressure and flow on the sprinkler heads and thus reduces the overall system water consumption. This allows a single water tank to serve more floors with the same volume water tank as compared to a system which does not constrict its pipe diameters.

It is recommended to use at least two water tanks in a high-rise building. The first tank is placed at the optimal height above the heavier hazard classifications typically found on the lowest floors. The second tank is placed on the floor and protects all the lighter hazard floors up until the first tank reaches the minimum required height difference. The heavier hazard classifications require a larger water tank, which also means that the increase in water tank size due to higher dynamic pressure is also much greater when compared to the much smaller water tanks needed to protect the lighter hazard classifications. This means the second will need to be larger as it protects more floors. But this size increase is much less than if the first tank were to be placed higher or a single tank is used to protect the entire building.

The structure surrounding the water tanks must also be reinforced to bear the heightened load of the water within the water tank. It is recommended that this be accomplished by utilising the support columns and load-bearing divider walls to create a box within the building that can house the water tank. The divider walls create a localised area where the floor can handle the increased load from the water tank. Another divider wall can also be used within the box to compartmentalize the water tank. Furthermore, water tanks placed at altitude may interfere with dampening devices within the building, as free flowing water in such quantities may instead enhance vibrations within the building. As it is yet not known the influence that these water tanks may have on vibrations, it is recommended to investigate the effects of water tanks placed at altitude within a building on vibrations of said building.

Reflection

Looking back at the progress and results of this research, I am quite pleased. The prior experience I was able to obtain working as a junior engineer within the fire safety and security team at RHDHV allowed me to start this research with a clear idea of the objectives and path to take to fulfil those objectives. This research has stimulated me to dive even deeper into the normative frameworks and design process that stands at the core of fire safety. It is knowledge that has helped me prepare for my departure from academia and entrance into my job, post-graduation. I have gained a much deeper understanding of performing hydraulic analysis and specifically using SprinkCALC. I have learned the difference between calculating the supply and demand of a sprinkler as well as gained a deeper understanding how factors like spray density and pressure influence one another.

Furthermore, this research has challenged me in areas where I still consider there to be room for growth. The first is report writing, which is a skill that I could still improve upon. It is also something that I do not have a particular aptitude for. It is the reason behind most procrastination that I have experienced over the course of this research. Though I was able to uphold the planning that I made at the beginning, there are many times I wish I could have been more productive. This is an area of improvement that I have been working on for many years now. But I think that I have been better able to motivate myself, specifically in those times where I found it hard to do so. I have also been able to improve my report writing skills, due to the increased demands of a thesis compared to previous reports. My coaching lecturer was very helpful in specific areas of reports that deserved additional attention. I now better understand how to be consistent in my terminology as well as maintaining a better balance between high-level and detailed information. In the future I hope to further improve in this regard so that I can more easily bring across my message in written as well as spoken context.

My experience of being well-oriented at the start was quite pleasant and allowed me to get a head-start. Therefore, I plan on starting future projects and research in similar fashion. To do so, I intend to start by looking into all relevant topics for the project to allow myself to correctly define the objectives and create a planning accordingly. The literature review specifically, was a point of difficulty for this research. I had trouble finding relevant sources specific to gravity-feed systems for fire sprinkler systems. After searching multiple databases, I instead pivoted my attention to the agrarian sector instead as gravity-feed systems. This allowed to find sufficient information relevant to the research. However, in the future I intend to spend more time earlier on in the research on the literature review. Had I done it during this research, I might have been able to find more relevant research. Furthermore, I plan to continue to work on motivating myself to tackle those areas of projects that I find hard to complete. Ultimately, I would like to be able to be more continuously productive rather than to be very productive in short bursts.

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A1 Detailed flow chart of report elements

Below in Figure 14 is the detailed version of the flow chart of report elements shown in Section 2.2. It shows the steps taken within each chapter and the phase of the research it is associated with it. Furthermore, it shows the relation between chapters, with the arrows how the results of one chapter are used in other chapters.

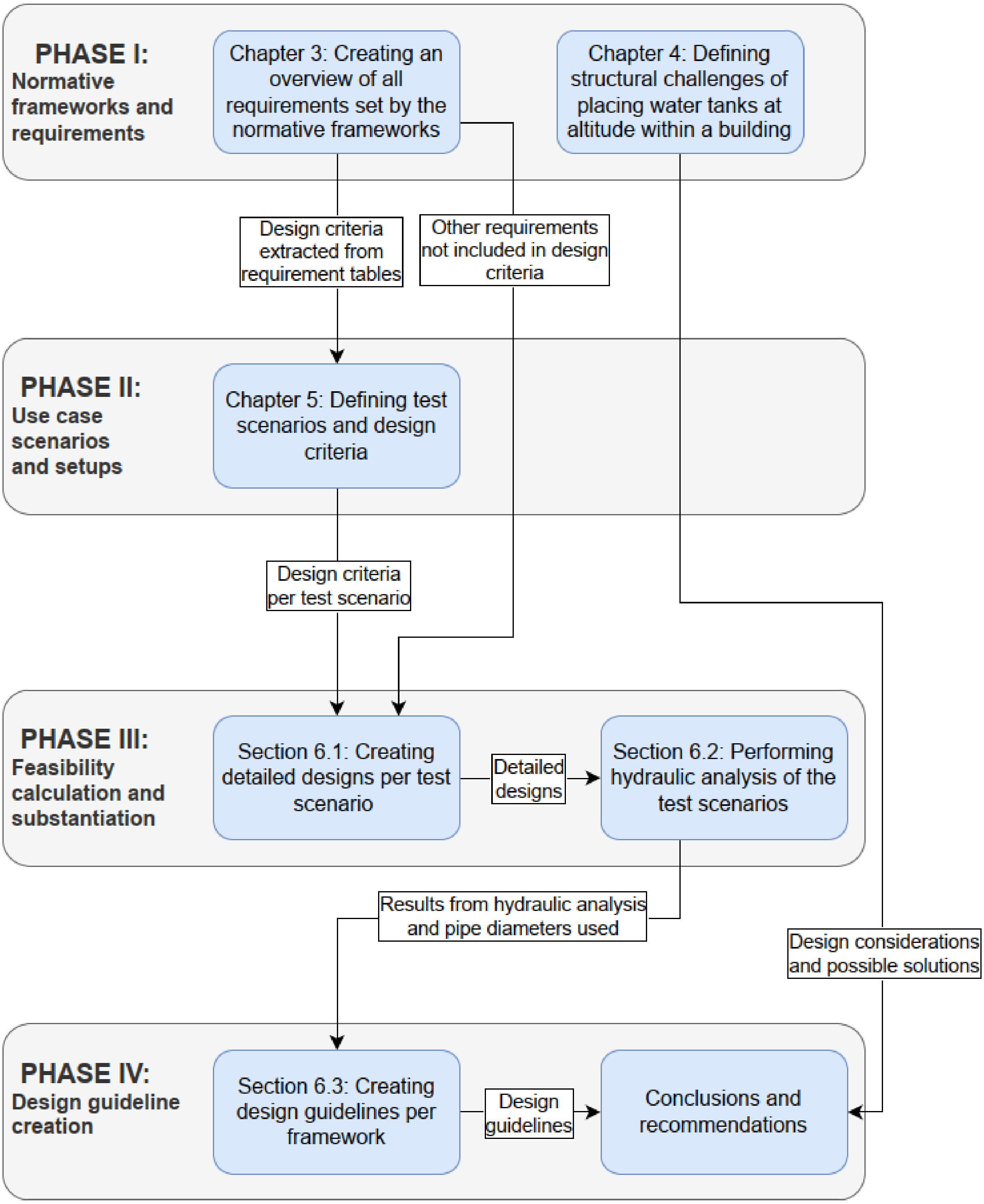

Figure 14: Detailed flow chart of report elements

A2 Mock building basic design drawings

Below are the detailed drawings of the basic design for the mock building used in the test scenario calculations in Section 5.1. The first drawing is a cross-section of the building showing the different floors and the height of floors (Figure 15). The basement up to the fourth floor are all four meters in height. Above the third floor, each floor is 3,6 meters in height. The total height of the mock building is not set, as the maximum height difference between the gravity tank and sprinkler zone is also calculated. The second drawing is the general floor plan with two staircases on either side of the building (Figure 16). The left staircase also has an adjoining utility room which contains the sprinkler system riser which supplies the sprinklers on the floor. Next to the riser is the floor control assembly, which every floor contains. It consists of a control valve with a flow switch and an accompanying test and drain connections.

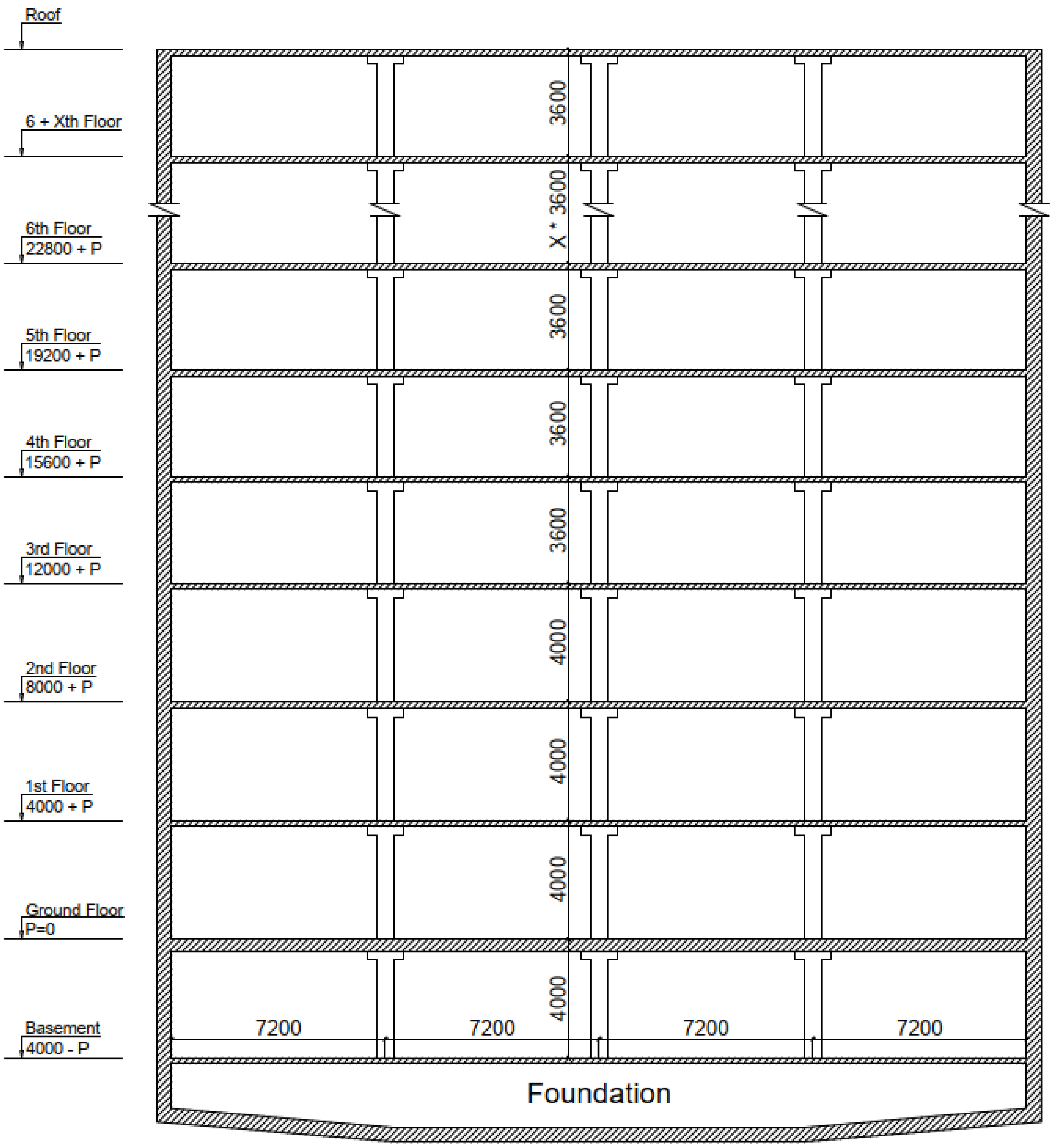

Figure 15: Enlarged version of mock building cross section

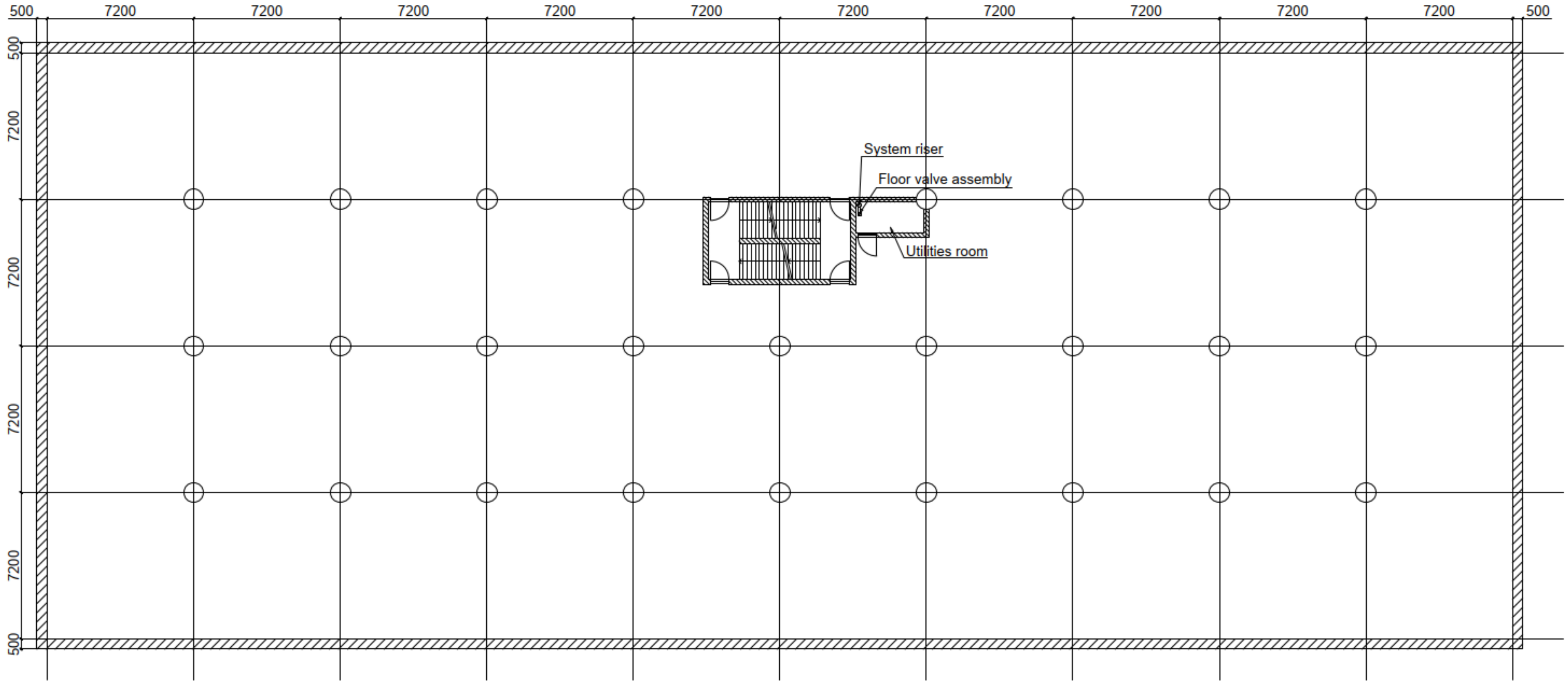

Figure 16: Enlarged version of the basic floor plan of the mock building

A3 Detailed system designs for test scenarios

This appendix contains all of the detailed design drawings made for the test scenarios as discussed in Section 6.1. Each test scenario has three detailed designs, one for each normative framework. The detailed drawings contain the unfavourable areas, and for NEN also the favourable area which have been used to calculate the design criteria for gravity-feed systems per hazard classification per normative framework. Each drawing contains the following elements:

- Walls and doors in the colour indigo,
- Furniture, floor markings, and other non-structural elements in brown,
- The initial pipe diameters calculated for the system are shown next to the pipes,
- Distance between sprinklers and other components are shown with red lines and the distance in meters rounded to a tenth,
- Sprinkler components for NEN in green,
- Sprinkler components for NFPA in red, and
- Sprinkler components for FM Global in light blue.

A3.1 Scenario 1: Residential detailed designs

Scenario 1 covers the residential areas that are often found on the upper floors of a high-rise building. The detailed design drawings for this scenario can be seen in Figure 17 for NEN, Figure 18 for NFPA, and Figure 19 for FM Global below. The unfavourable area has been placed in the bottom left corner of the floor, as this is the furthest away from the system riser in the shaft. The favourable area for NEN has been placed in the residence above the shaft as the hallway exceeds the 126m² limit for LH.

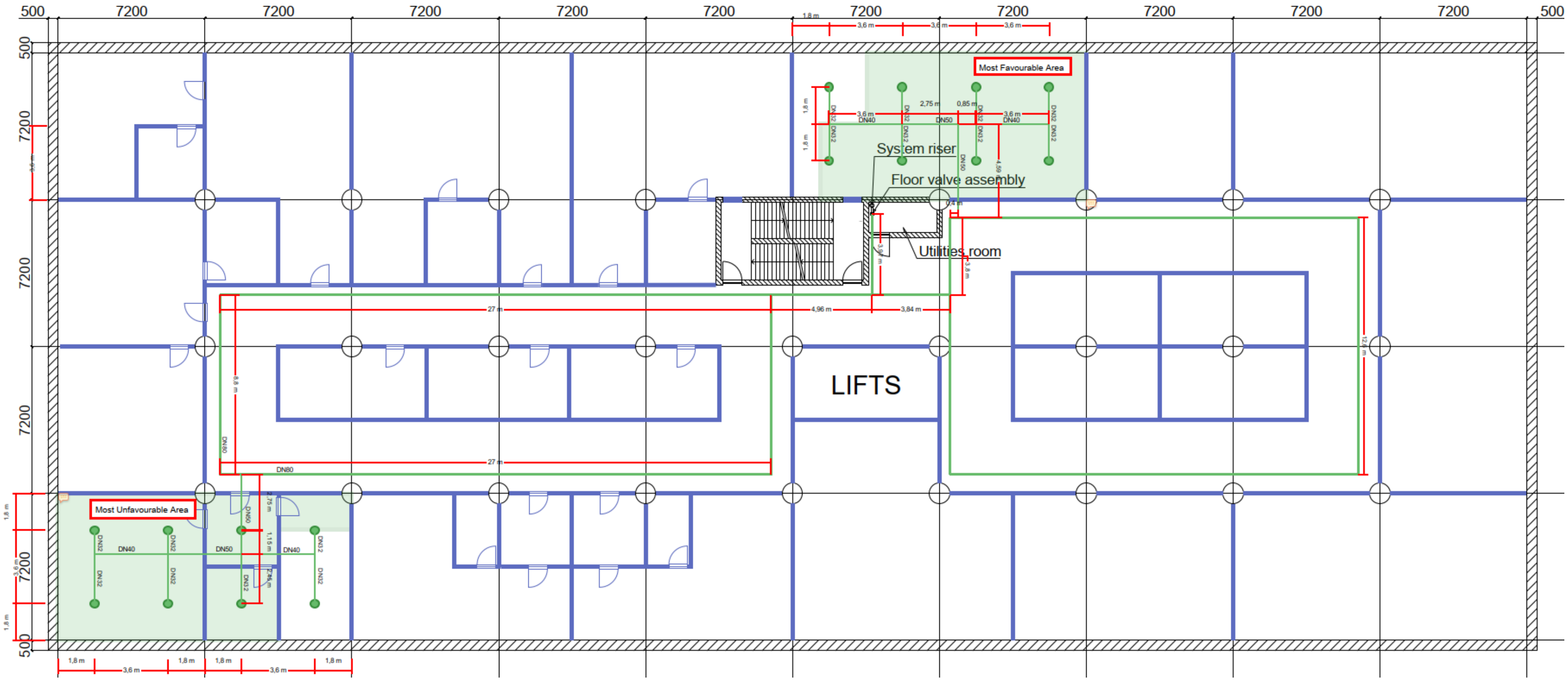

Figure 17: Detailed design of the NEN system for Scenario 1: Residential

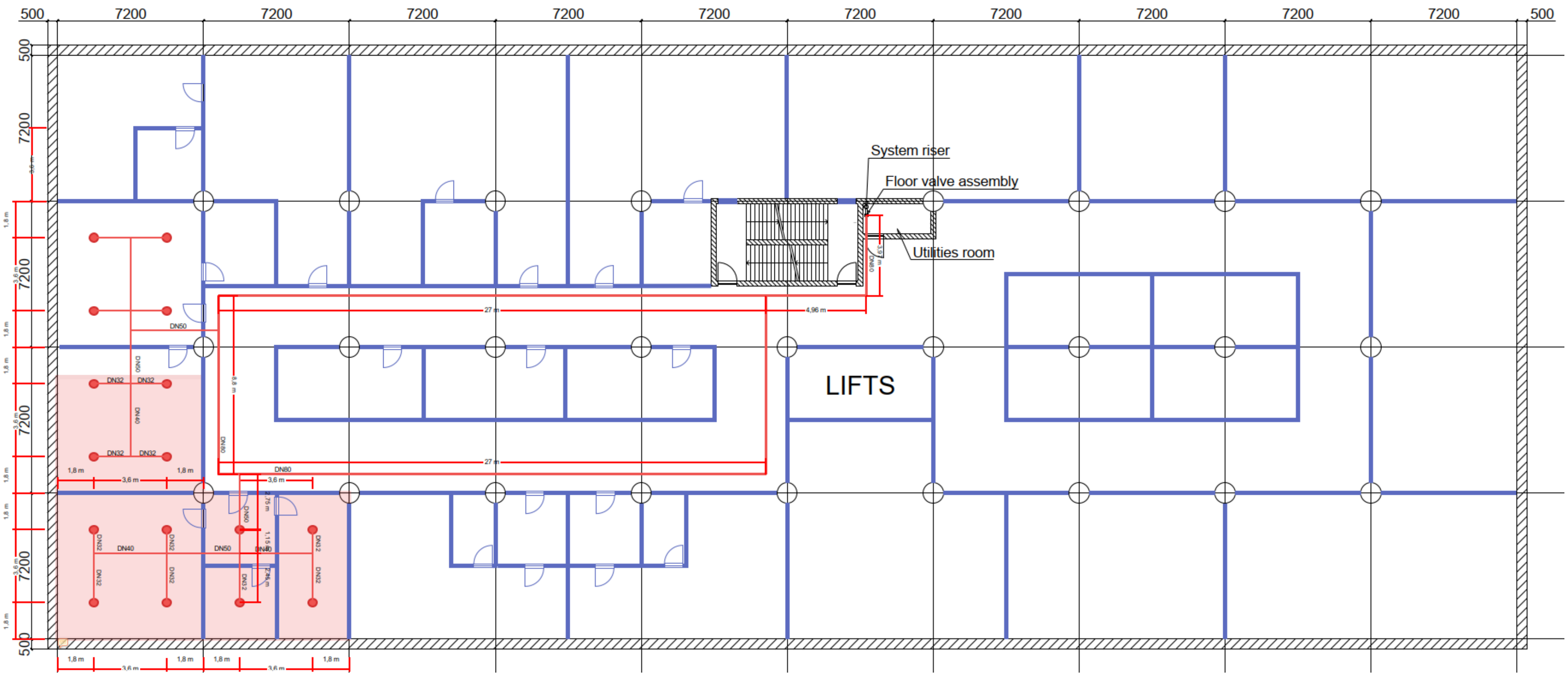

Figure 18: Detailed design of the NFPA system for Scenario 1: Residential

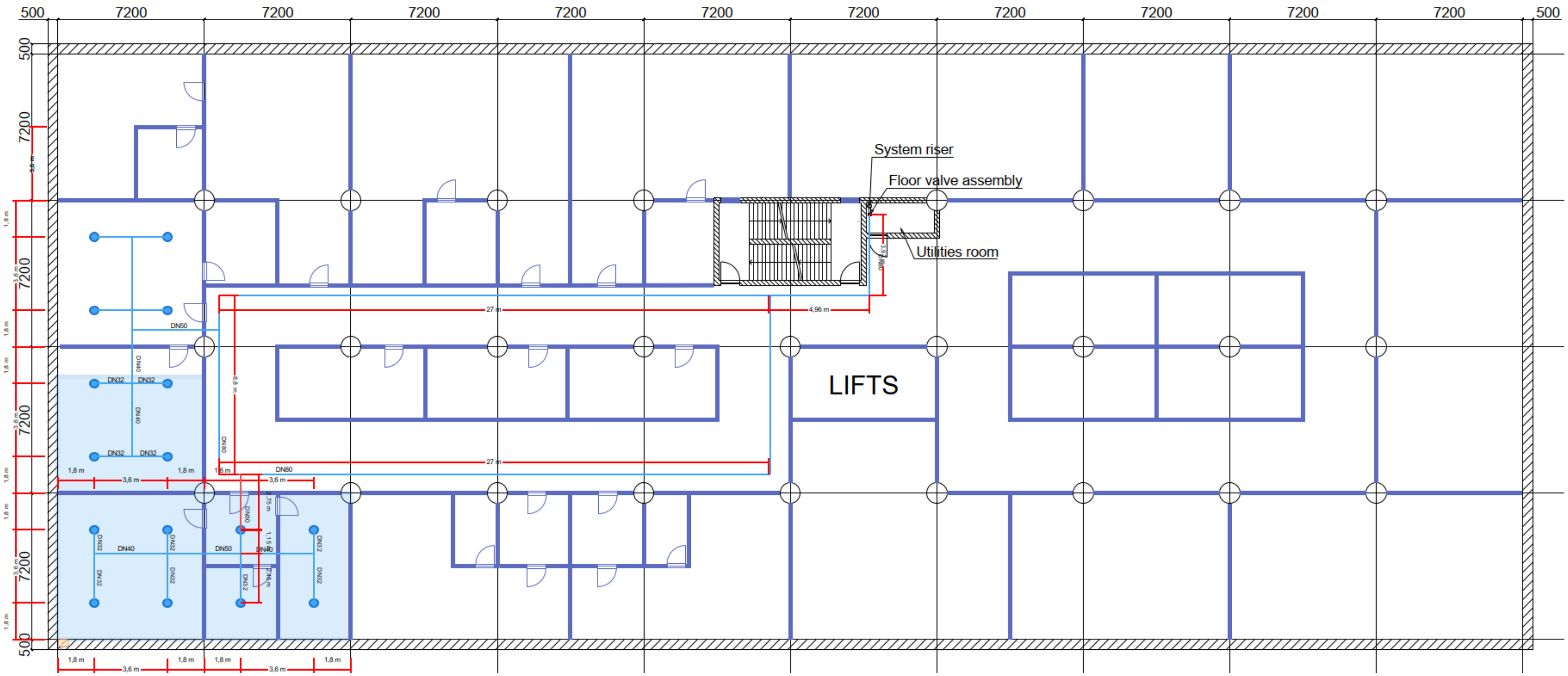

Figure 19: Detailed design of the FM Global system for Scenario 1: Residential

A3.2 Scenario 2: Offices detailed designs

Scenario 2 covers the office areas that are often found on the upper floors of a high-rise building. The detailed design drawings for this scenario can be seen in Figure 20 for NEN, Figure 21 for NFPA, and Figure 22Figure 19 for FM Global below. The unfavourable area has been placed in the bottom left corner of the floor, as this is the furthest away from the system riser in the shaft. The favourable area for NEN has been placed in the hallway below the shaft.

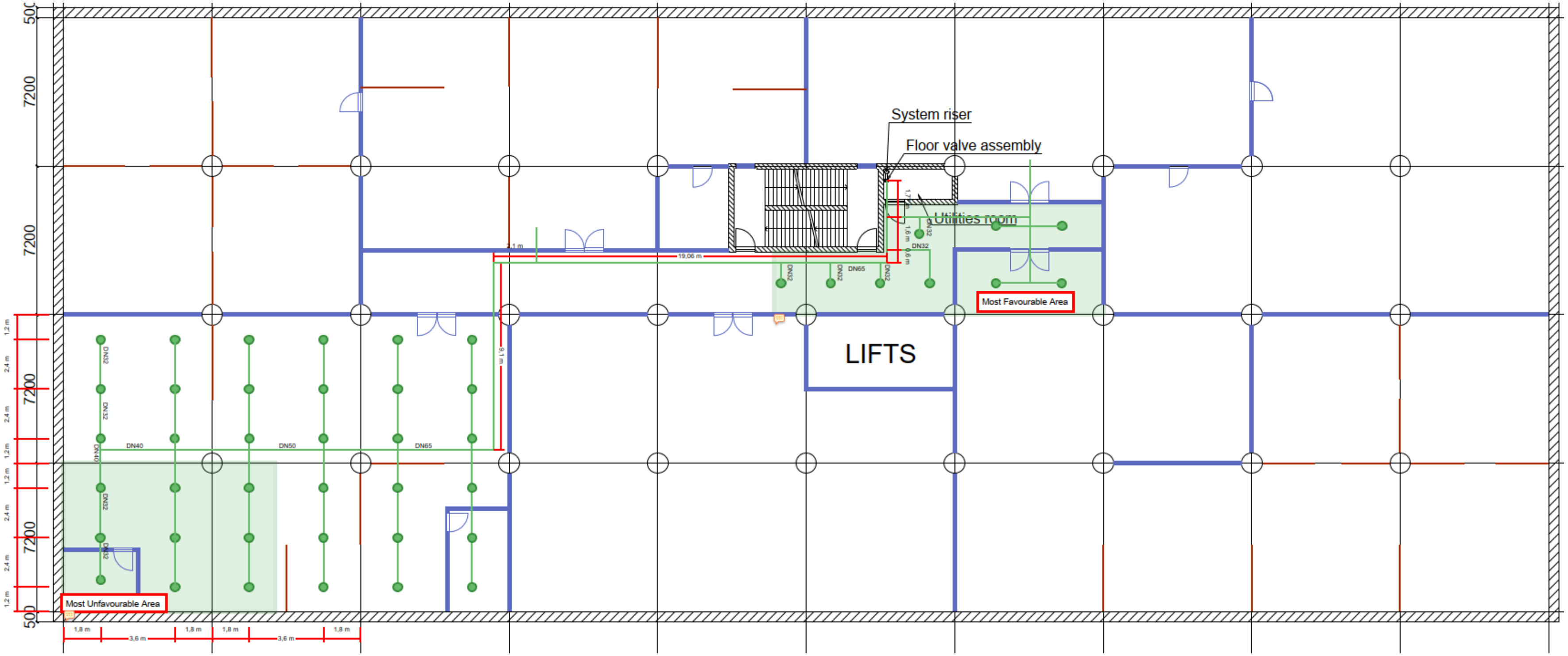

Figure 20: Detailed design of the NEN system for Scenario 2: Offices

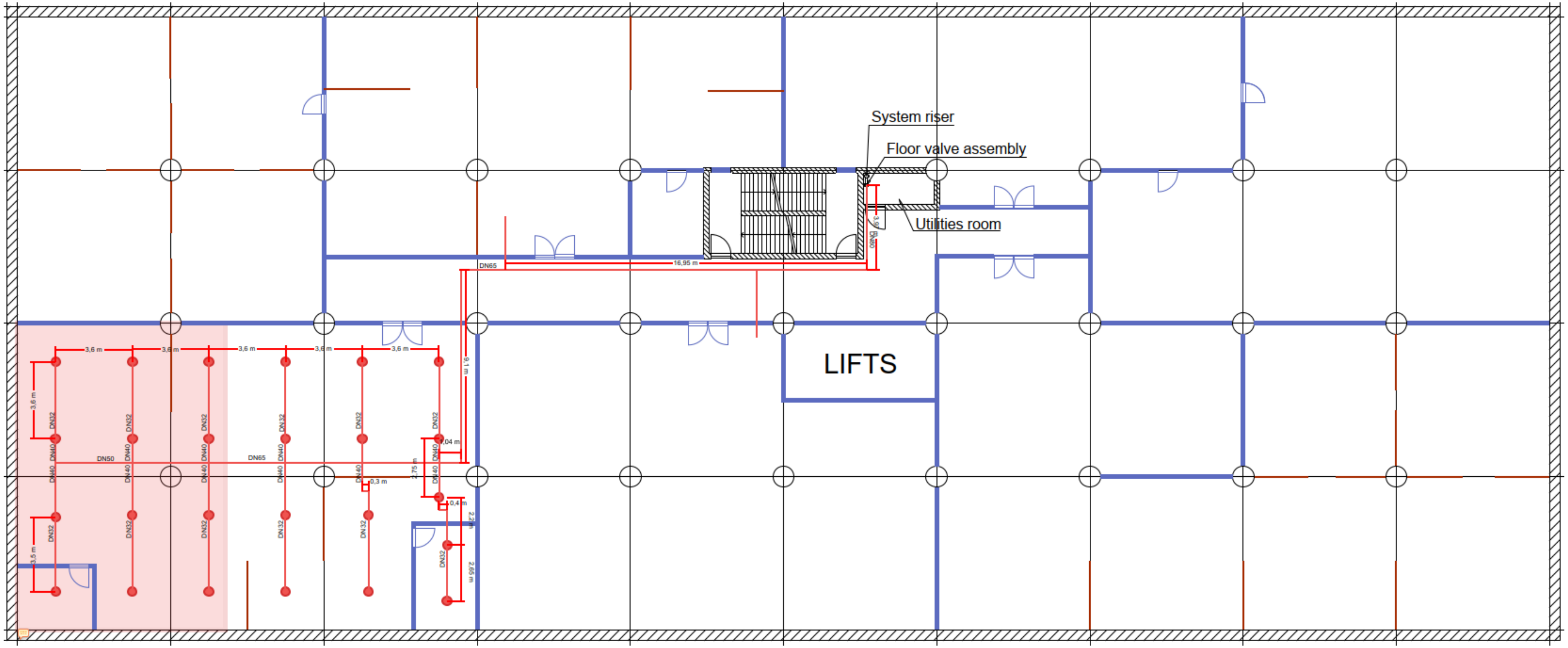

Figure 21: Detailed design of the NFPA system for Scenario 2: Offices

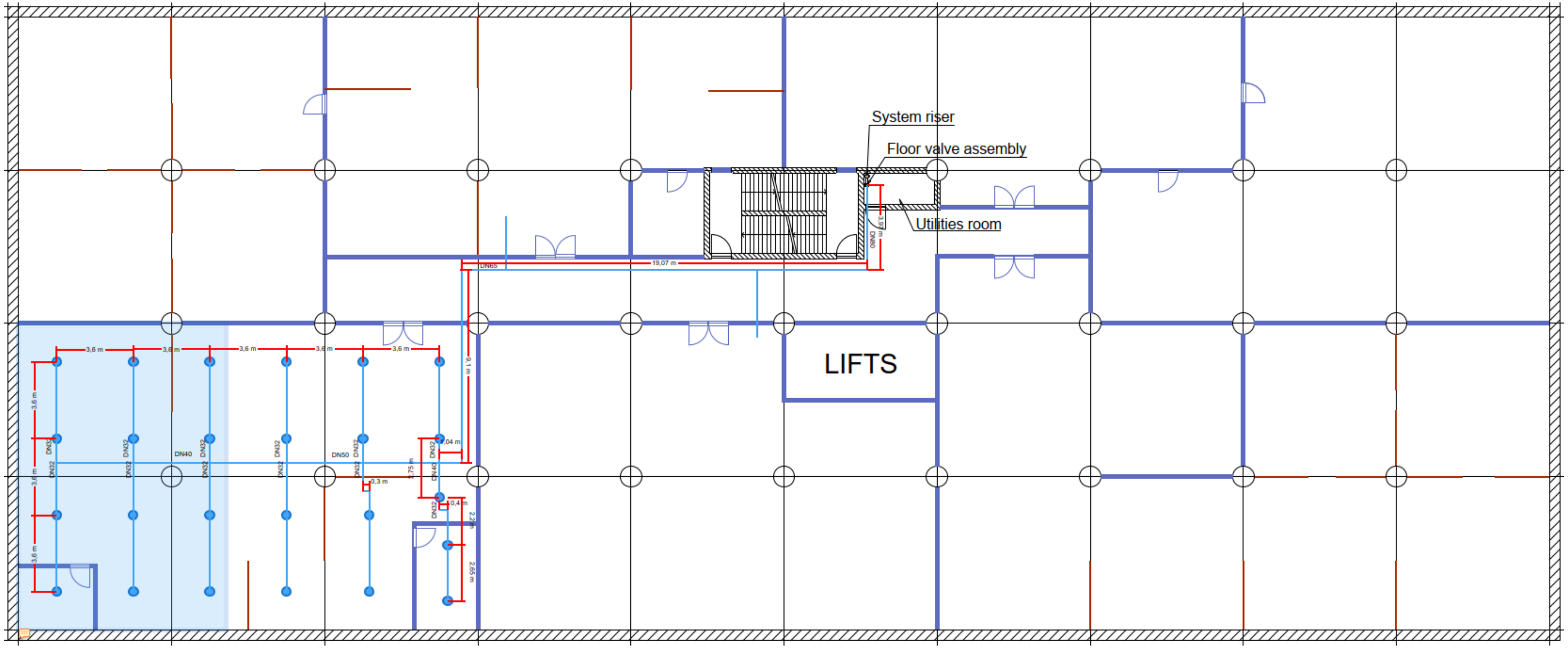

Figure 22: Detailed design of the FM Global system for Scenario 2: Offices

A3.3 Scenario 3: Underground parking garage detailed designs

Scenario 3 covers the underground parking garage that are often found present below a high-rise building. The detailed design drawings for this scenario can be seen in Figure 23 for NEN, Figure 24 for NFPA, and Figure 25 for FM Global below. The unfavourable area has been placed on the left side of the floor, as this is the furthest away from the system riser in the shaft. The favourable area for NEN has been placed outside the central hall on the right.

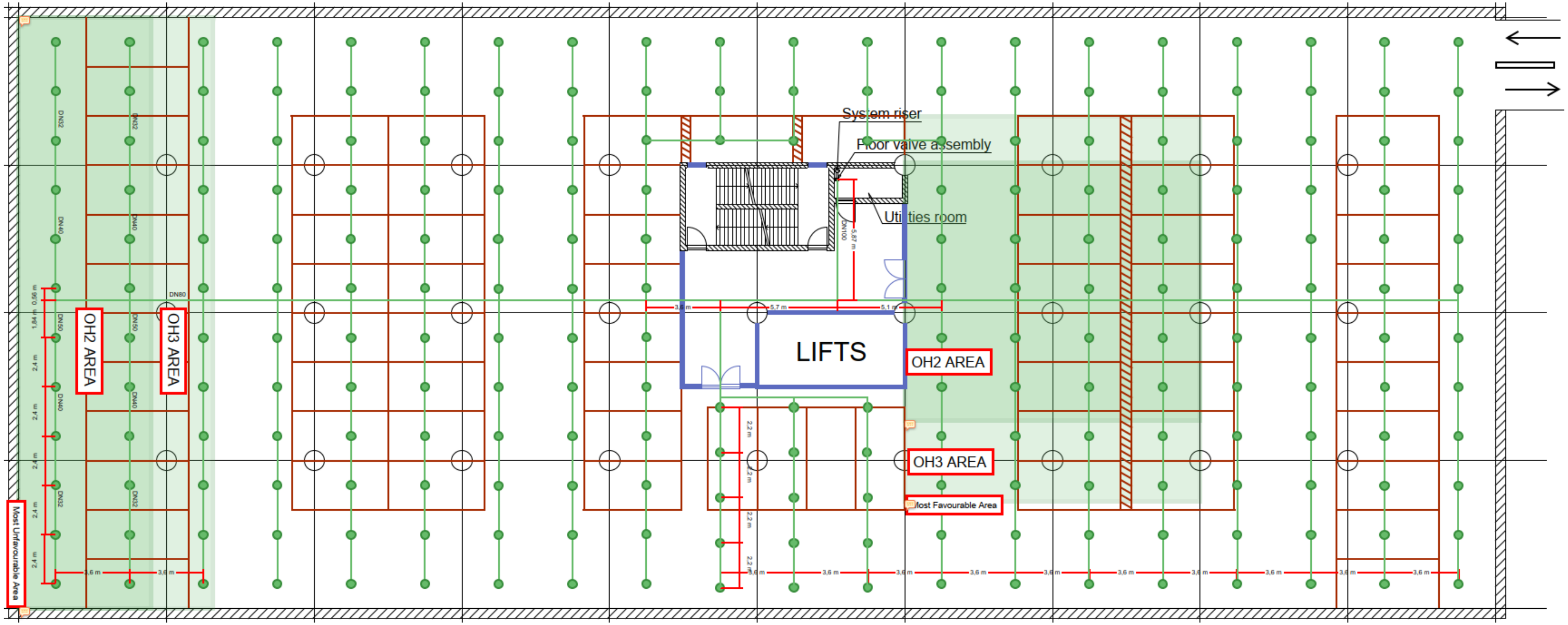

Figure 23: Detailed design of the NEN system for Scenario 3: Underground parking garage

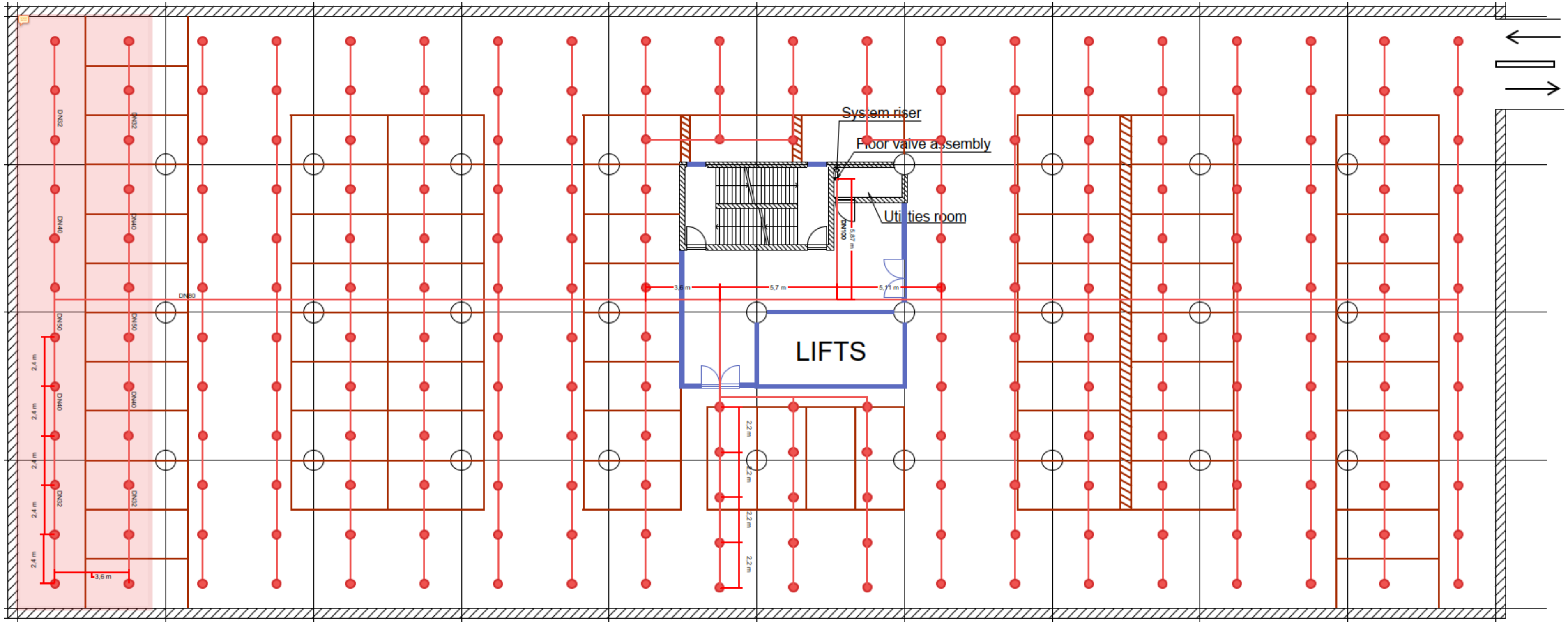

Figure 24: Detailed design of the NFPA system for Scenario 3: Underground parking garage

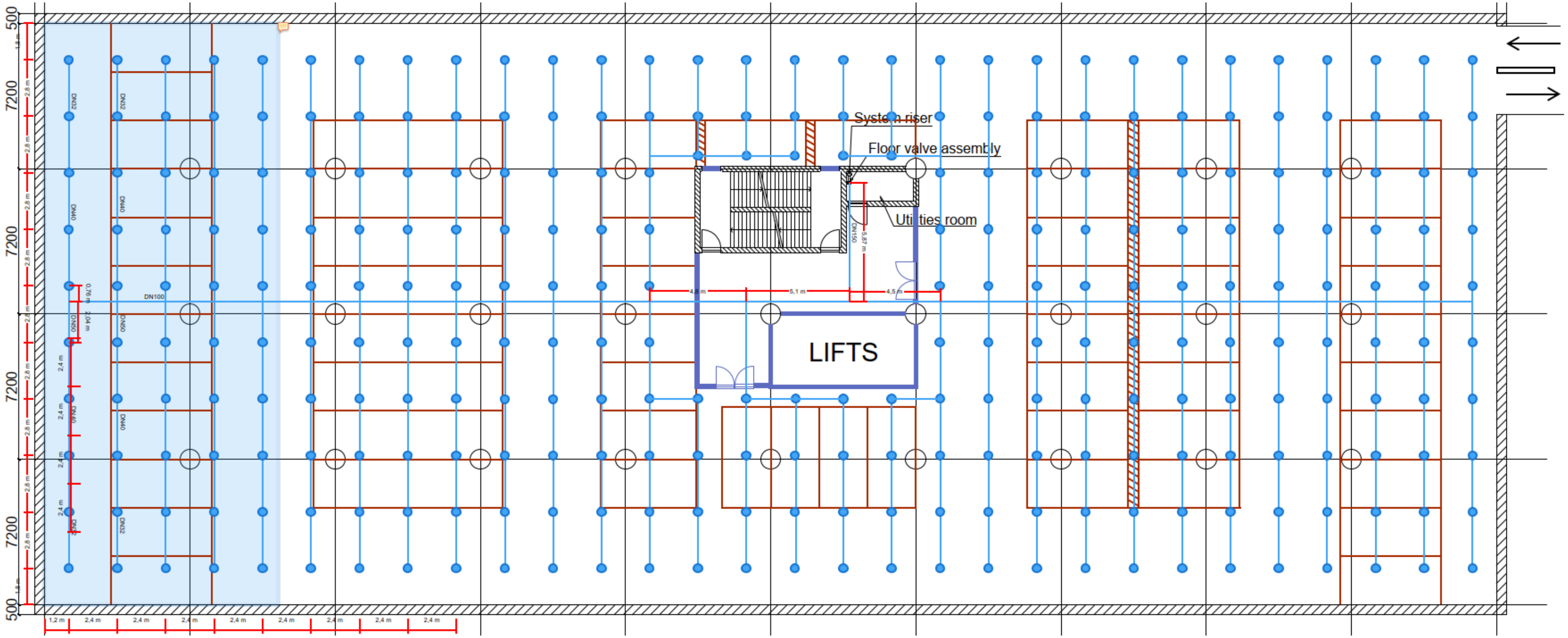

Figure 25: Detailed design of the FM Global system for Scenario 3: Underground parking garage

A3.4 Scenario 4: Grocery store and Scenario 5: Bakery detailed designs

Scenarios 4 and 5 cover the mercantile occupancies that may be present on the ground floor of a high-rise building. It consists of a grocery store in the bottom left corner and a bakery in the top left corner. The detailed design drawings for the scenarios can be seen in Figure 26 for NEN, Figure 27 for NFPA, and Figure 28 for FM Global below. The unfavourable area has been placed on the left side of the floor, as this is the furthest away from the system riser in the shaft. The favourable area for NEN has been placed on the right side of the occupancy.

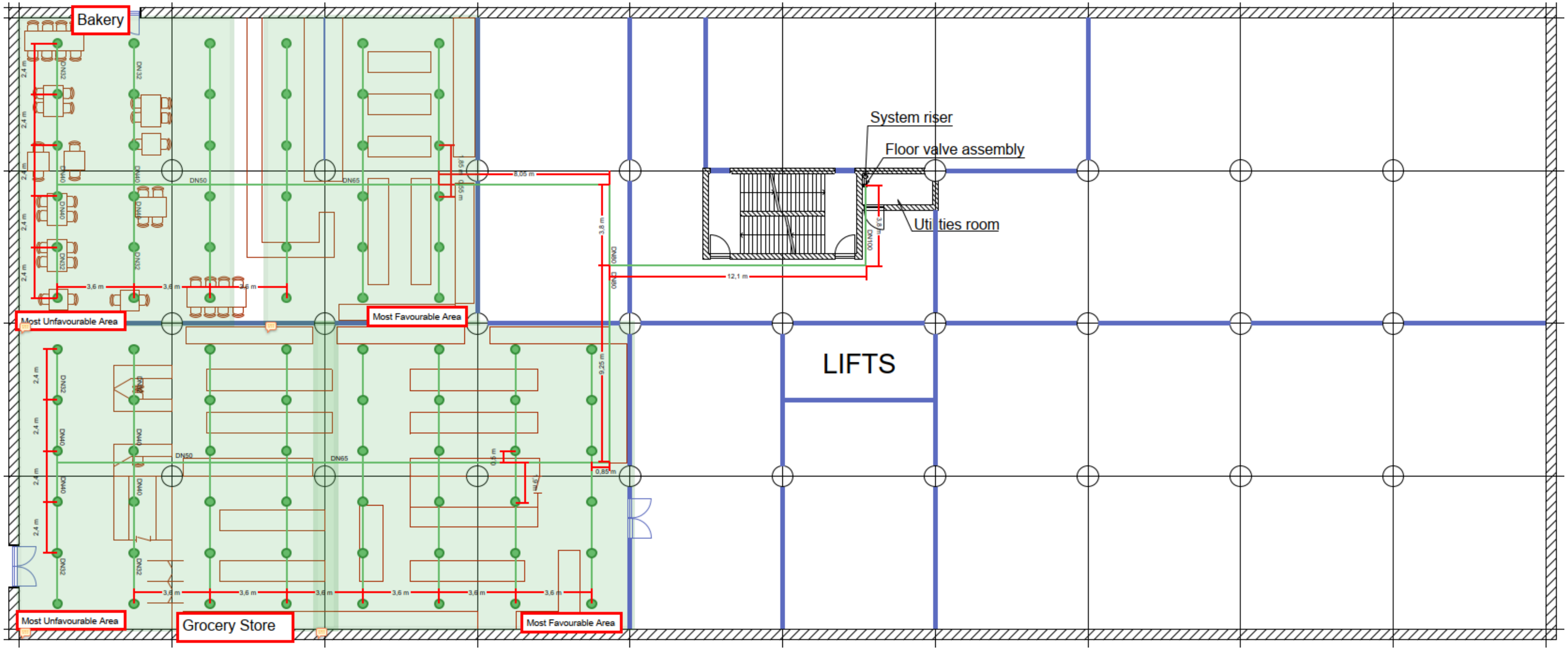

Figure 26: Detailed design of the NEN system for Scenario 4: Grocery store and Scenario 5: Bakery

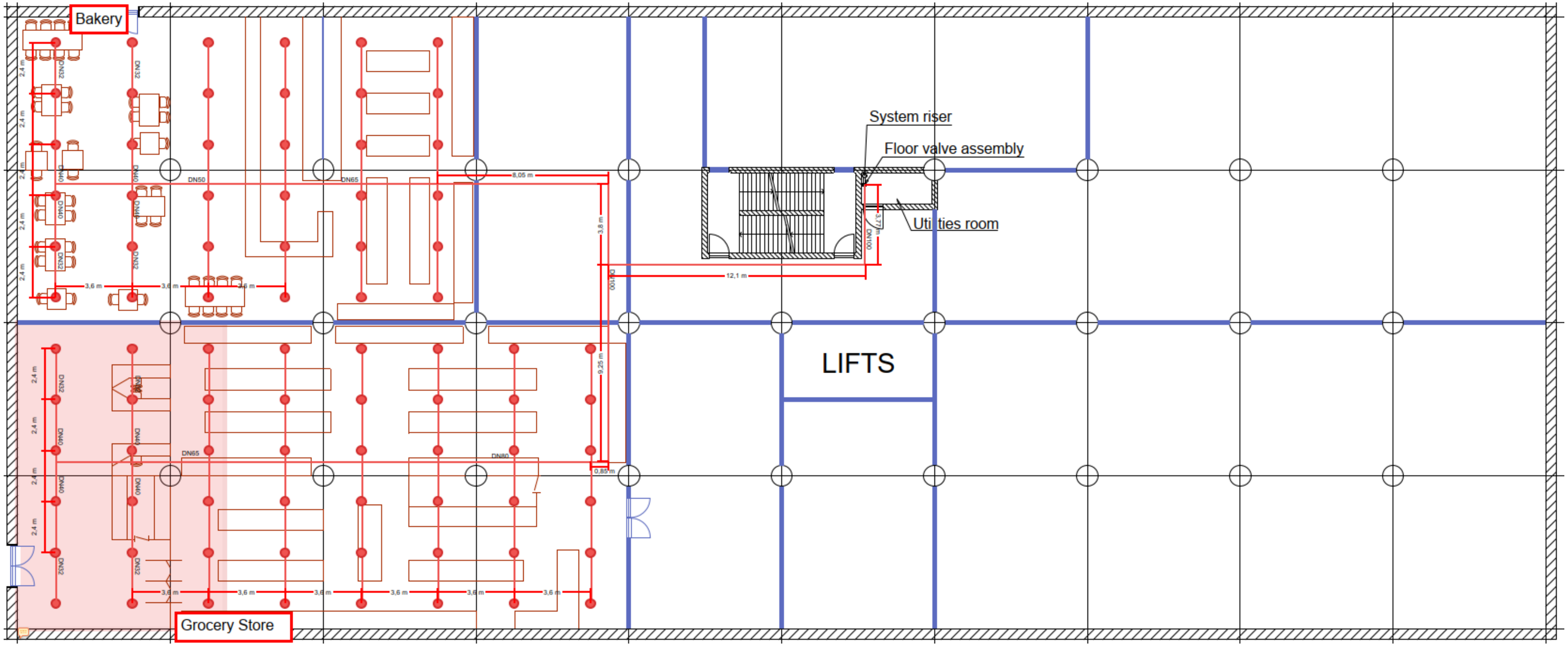

Figure 27: Detailed design of the NFPA system for Scenario 4: Grocery store and Scenario 5: Bakery

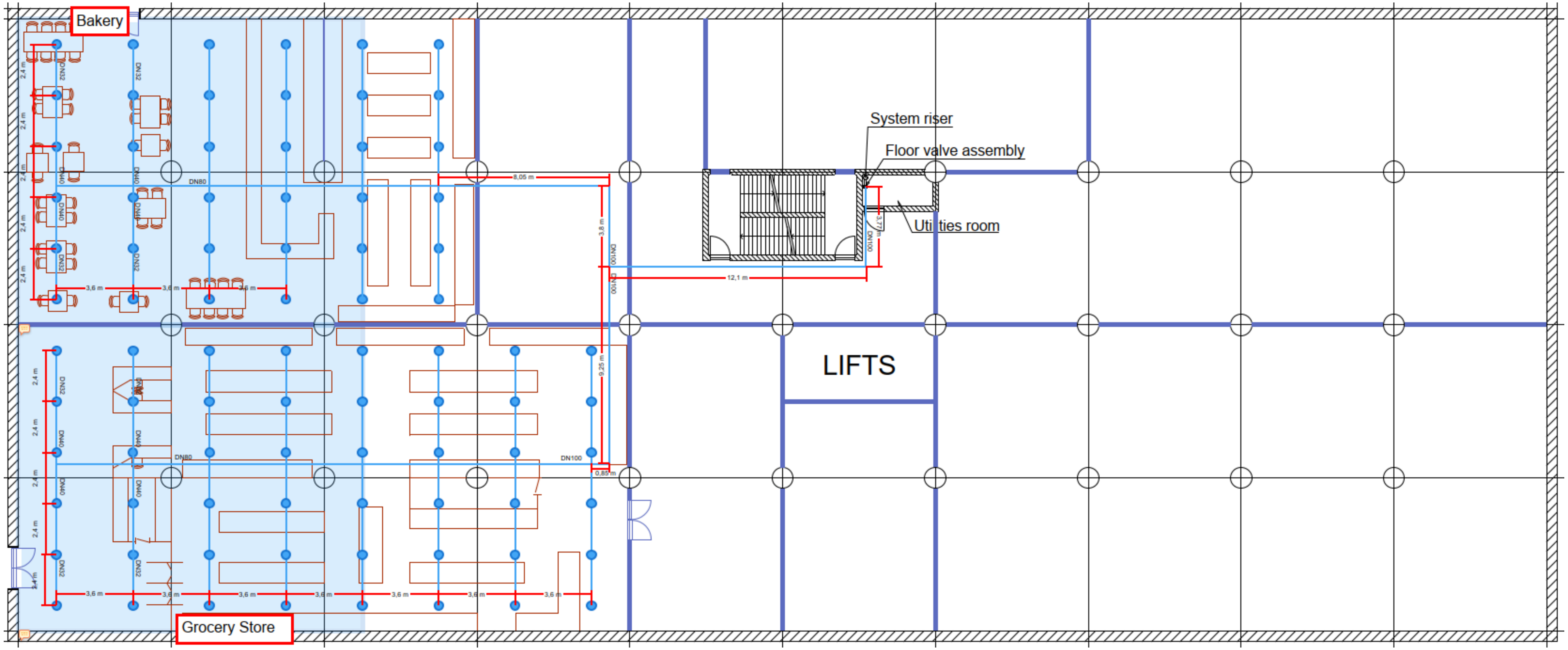

Figure 28: Detailed design of the FM Global system for Scenario 4: Grocery store and Scenario 5: Bakery

A3.5 Scenario 6: Cinema theatre detailed designs

Scenario 6 covers a cinema theatre that may be on the ground floor of a high-rise building. The detailed design drawings for this scenario can be seen in Figure 29 for NEN, Figure 30 for NFPA, and Figure 31 for FM Global below. The unfavourable area has been placed on the left and bottom left for FM Global and NFPA respectively. The unfavourable area for NEN has been placed on the right side of the cinema as it was found during hydraulic analysis to be more demanding upon the system. The favourable area for NEN has been placed on the left side instead.

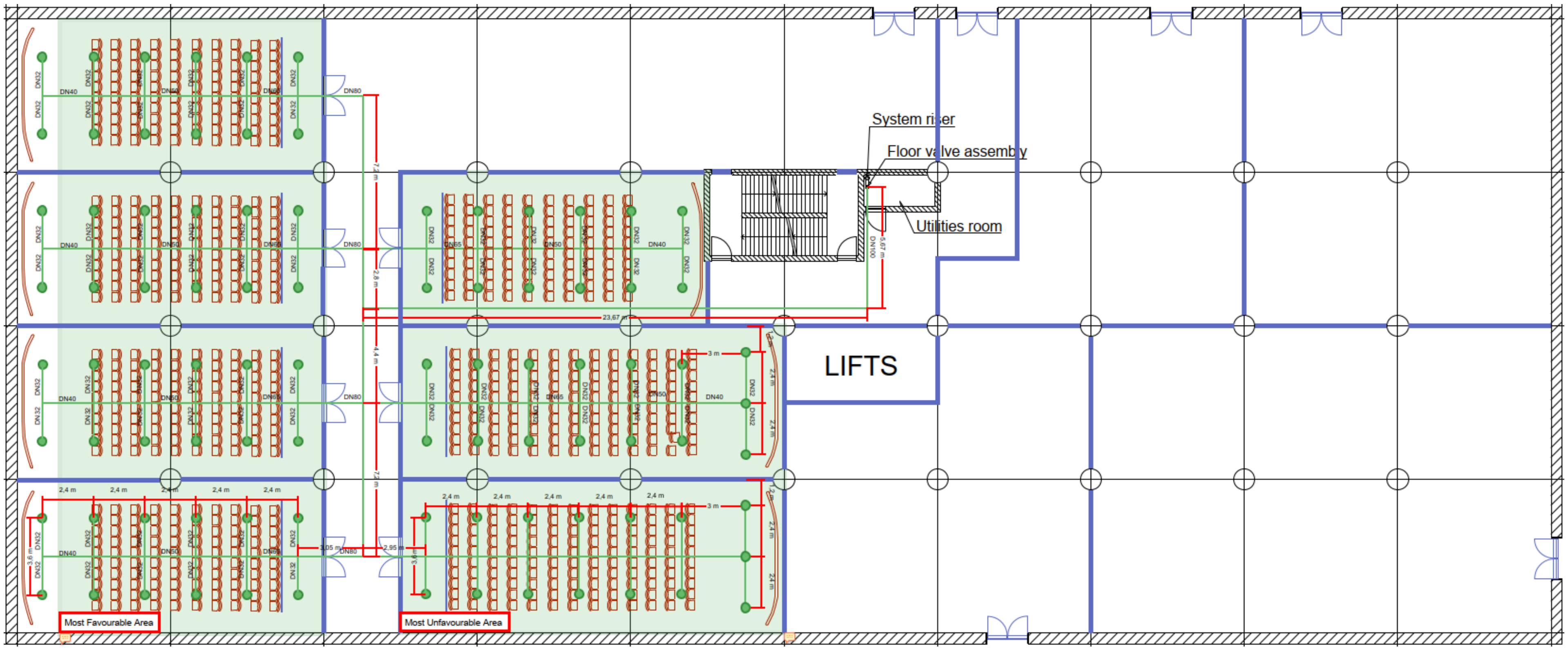

Figure 29: Detailed design of the NEN system for Scenario 6: Cinema theatre

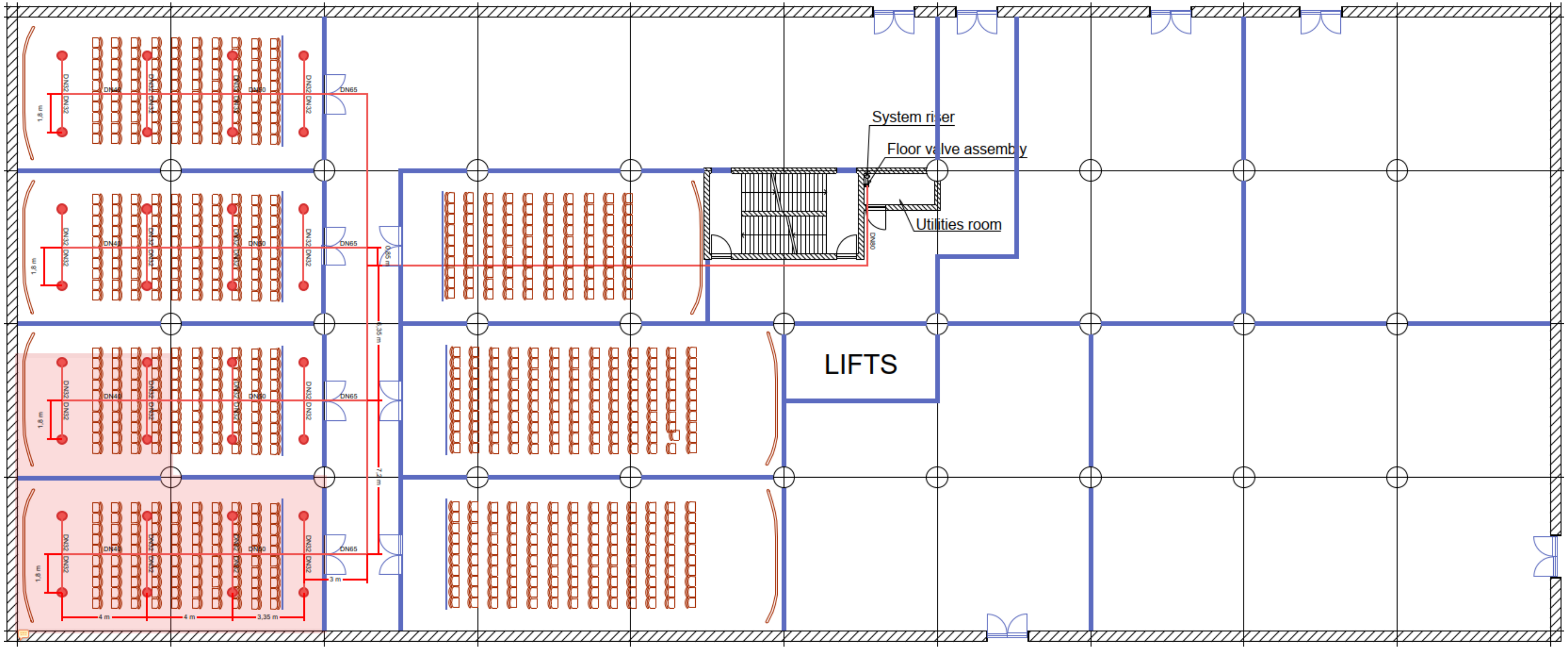

Figure 30: Detailed design of the NFPA system for Scenario 6: Cinema theatre

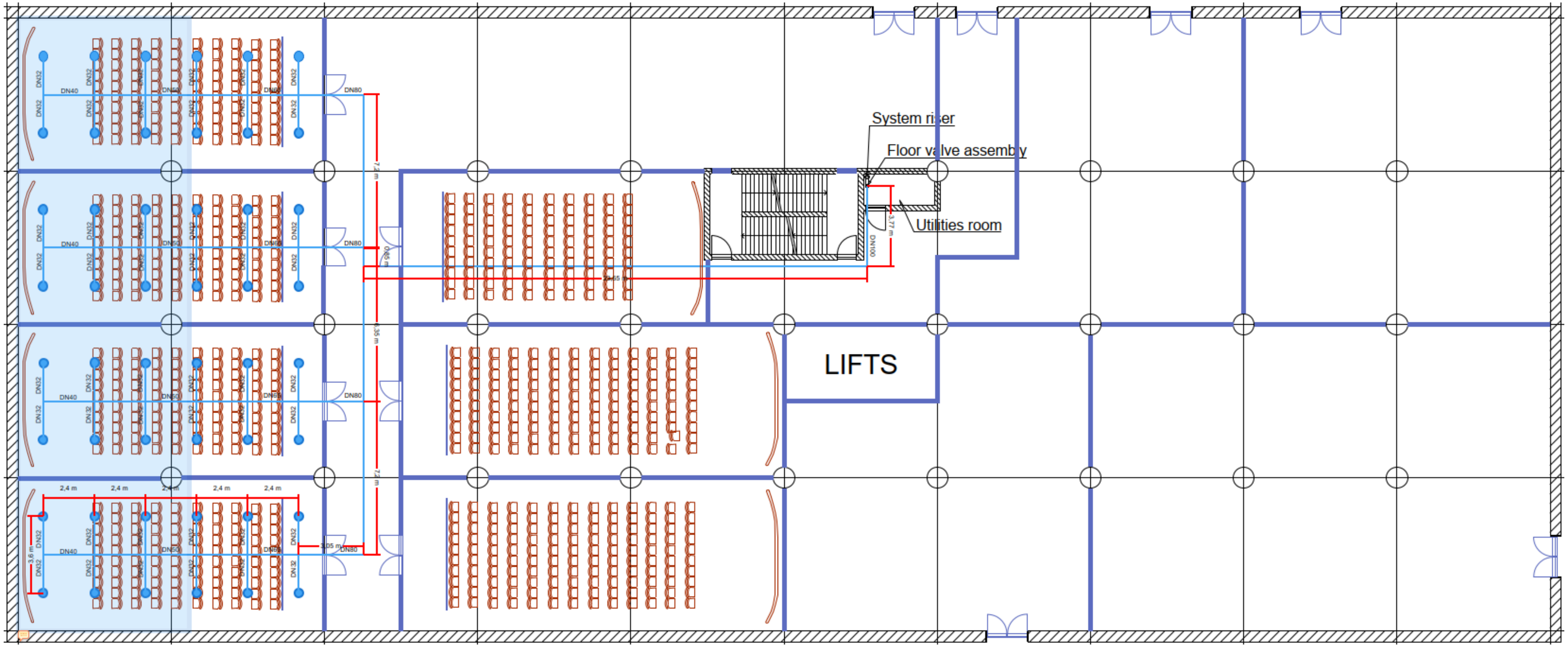

Figure 31: Detailed design of the FM Global system for Scenario 6: Cinema theatre