Assessing the risk of flanking of thermally light facades in case of fire: a case study

Author: N.H. (Nora) Kuiper
Supervisor: ir. R.A.P. (Ruud) van Herpen

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Eindhoven University of Technology

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1. Introduction

To house the growing population, the construction rate is as high as ever. Lots of new buildings are realized; older buildings are being renovated to conform to modern building standards. At the same time, the building technology is changing along with the innovation of new building materials. This has brought many new opportunities regarding building and design, but also new challenges and threats, e.g. regarding the fire safety.

One of these threats is fire spread by flanking. Flanking fires can be defined as the spread of fire via the facade of a building, propagating via the outside or through a cavity. This way, a flanking fire will shortcut the fire compartmentation and accelerates fire spread to other compartments and throughout a building. This phenomenon has become a topic of great interest over the past five years, especially after the deadly fire in the Grenfell tower that took place in London, in June 2017. The Grenfell tower, a 24-storey building built between 1972 and 1974, was renovated between 2012 and 2016. In 2017, a fire started in the kitchen of one of the apartments on the fourth floor. Within 15 minutes, the fire in the apartment resulted in an external flame and approximately 18 minutes after the fire had reached the facade, the fire had spread to all other floors above the fourth floor. The spread of fire via the facade, along with inadequate "Stay put"-instructions by the fire brigade, resulted in 72 fatal casualties and 74 non-fatal casualties [1].

Many other incidents have been linked to the flanking fire that destroyed the Grenfell tower. In Chapter 2, "Background", the report goes further into depth on these links, especially regarding building materials and building technology. It explains how the fire safety of facades is tackled with respect to the regulations as set in the Dutch Building Code and with the respect to risk assessment. Chapter 3 explains the research objective and briefly introduces the case study. The case study on "De Ananas", a new residential complex in Leiden that is currently still under construction, is reflected upon in Chapter 4. The risk of flanking is analyzed for this specific case in OZone and COMSOL Multiphysics. Chapter 5, a similar COMSOL Multiphysics model is used to evaluate the other facade types that have contributed to flanking fires in the past. Design recommendations will be made based on the findings of this project, with respect to materialization and building technology and will be treated in Chapter 6. Finally, in Chapter 7, the conclusions based on all background information, the case study on "De Ananas" and the study on the other facade types will be presented.

2. Background

2.1 Regulations and risk assessment

Dutch Building Code

Regulations regarding the fire safety of buildings are found in the Dutch Building Code. The regulations have two main goals in the event of fire, namely limiting the amount of casualties (injured or deadly) and limiting damage to property of third parties. The corresponding functional requirements can be categorized within five sub goals: the fire safety of the environment, the fire safety of the structure of the building, the fire safety of the compartment regarding smoke and fire spread, the fire safety of the escape routes for the occupants and the fire safety of the attack routes for the fire brigade [2].

The sub goals can be quantified in acceptable failure probabilities. The acceptable failure probabilities are not described in the Dutch Building Code, but are implicitly set as (minimum) values to with a building or element should conform. If a building or element does not meet the requirements of one of the sub goals, it implies that the building needs to perform better for the other sub goals to guarantee a safe space for occupants and prevention of damage to property of third parties in the event of fire [2].

Article 2.84 in the Dutch Building Code specifies regulations regarding the fire safety of compartments in the WBDBO ("Weerstand tegen branddoorslag en brandoverslag"). This article sets requirements for the resistance of the construction against fire spread via the direct route (in Dutch: "branddoorslag"; i.e. via partition walls and floors) and for the resistance against fire spread via the outdoor route via daylight openings (in Dutch: "brandoverslag", i.e. fire spread around the direct route). For residential buildings, the fire resistance of the construction between two neighboring apartments should be at least 60 minutes, both via the direct route and the indirect route. Exception is based on the symmetry rule: a facade conforms to the WBDBO if both the fire resistance of the construction from indoors to outdoors is 30 minutes and the fire resistance of the construction from outdoors to indoors is 30 minutes [3].

Additionally, to prevent facades from being ignited when exposed to external flames in case of a compartment fire or when exposed to an outdoor fire close to the facade, the outermost facade layer should conform to a certain fire class. The fire classes have been determined by NEN 13501-1. In general, the outer layer of a facade has to conform to fire class B. This implies that the material barely contributes to a fire and that it is hardly flammable. Only materials that have fire classes A1 and A2 are performing better: these materials are inflammable and therefore will not contribute to a fire at all [4], [5].

The two tests performed to determine the fire class of a material are the Small Flame-test (EN-ISO 11925-2) and the Single Burning Item (SBI)-test (EN 13823). During the tests, also the production of smoke and the production of burning droplets are observed and classified. The Small Flame-test is performed on material samples of 9 cm by 25 cm, which are exposed to a small flame. This test is used to observe whether the material ignites, promotes flame spread and produces (burning) droplets [6].

The SBI-test is used to determine the flame spread, heat release, smoke production and production of (burning) droplets of a material when applied in a construction. A corner-segment mockup is built of 1.5 m in height, 1.0 m and 0.5 m in width. This full size model consists of all details according to the application of the materials, thus also any seams, the mounting of the construction elements and the presence of a (ventilated) cavity are included. The mockup is exposed to a fire with the power of a commencing fire, representing a fire in e.g. a trash bin or a small piece of furniture. The rate of heat release (RHR) of this fire is 30 kW and this fire test lasts 20 minutes [6], [7].

However, it can be questioned how reliable these tests are, compared to exposure of an actual building fire and/or external flame. This as the thermal load in an external flame or outdoor fire is often much higher than the RHR of 30 kW that the facade is tested for; and also the duration of an external flame may be longer than 20 minutes. It is therefore that a risk of fire spread by a flanking fire should be considered, even more so for thermally thin facades. An elaboration on this topic will follow in the section on facade materialization.

Fire Safety Engineering

Conforming to the regulations as set in the Dutch Building Code is one way to consider the fire safety of buildings, and more specifically facades. Fire Safety Engineering (FSE) goes beyond these regulations by a risk-oriented approach. In FSE, risk induced by a fire is defined as the probability multiplied by the impact. The risk is therefore higher when the probability and/or the impact is larger [8]. The failure risk tree for compartment fires, found in Figure 1, has been designed to help illustrate which factors are especially relevant when considering the risk of fire spread by flanking fires. Please note that this event tree is only for explanatory purposes and solely offers a qualitative indication.

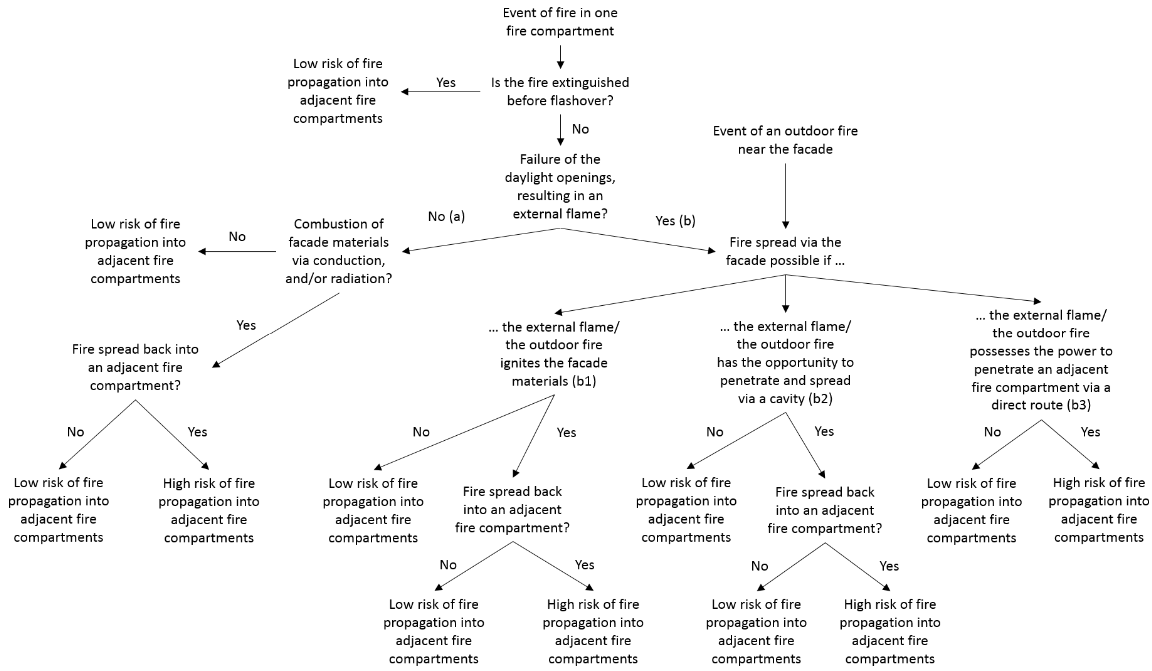


Figure 1. Failure risk tree for compartment fires

As mentioned prior, a fire inside one fire compartment can propagate to adjacent fire compartments via the direct route or via the indirect route. As the risk of flanking is the focus of this project, only the propagation via the indirect route will be considered for both indoor and outdoor fires.

Fire spread to adjacent fire compartments is possible after flashover, meaning that all fuel in the fire compartment has combusted. After flashover, two fire scenarios are considered: one in which the fire remains in the fire compartment where it started (scenario a), and one in which a daylight opening fails, resulting in an external flame (scenario b):

a. If the fire remains in the fire compartment where it started, it is unlikely that the fire directly threatens the facade (materials) via combustion. However, via convection, conduction and radiation, the heat produced by the fire can be transferred to combustible facade elements. This could potentially lead to combustion, once the ignition temperature of a material is reached. Without exposure to an actual flame, thus if only heat transfer is a potential cause of fire spread, this situation induces a low risk. However, if the facade material combusts due to the high temperature exposure, this should be considered as a potential high risk for adjacent fire compartments, depending on the likelihood of the fire spreading to other compartments.
b. If the fire causes the daylight opening to fail and external flaming occurs, three new routes are created for the fire to spread via the facade:
    1. If the materials in the facade are combustible, it is likely that these will set fire due to the exposure to the flame. This is possibly the most dangerous situation, making it possible for the fire to completely engulf the facade of a building within 15 minutes

(e.g. the fire in the Grenfell tower [1] or the fire Torre del Moro [9]). However, this is only problematic if the fire manages to penetrate into the other fire compartments. If the fire only burns up the facade, the personal safety of occupants of other fire departments is not in direct danger.

2. If the materials in the facade are not ignited by the spreading flame, there is a possibility that the fire will spread via the cavity (if there is any) [10]. By the chimney effect, a flame can easily reach up to 5 to 10 times higher in a cavity, if this cavity is not provided with fire- and/or cavity barriers (or provided with faulty ones (Grenfell, 2017 [11])) [12], [13]. More on this topic will be discussed in the next section. Again, fire spread via the cavity is only problematic if the fire manages to enter other fire compartments.
3. If there is no cavity and no combustible material in the facade, there is still a possibility that a fire can penetrate into the adjacent fire department via the facade or failure of the daylight opening of that fire compartment. The phenomenon of a fire breaking out via one daylight opening and reentering the building through windows above, is sometimes also referred to as the “leap-frog effect” [10], [14]. Subsequently, fire may spread vertically to all other floors above the initial fire, without combustion of the facade materials or fire spread through the cavity.

If a fire starts outdoors, e.g. by something s mall as a dumped cigarette butt or something larger as a container fire, the risk exists that a nearby facade ignites due to the heat release rate by the fire. According to the Dutch Building Code, this risk is minimized if the outer facade conforms to at least fire class B.

Whether a fire starts indoors or outdoors, it is most important to meet the main goals as mentioned before: ensure personal safety of the occupants and prevent material damage of third parties.

BZK facade fire risk tool

Since the fire in the Grenfell tower in London, more attention is paid to the fire safety of facades. In November 2018, the Dutch Ministry of the Interior and Kingdom Relations (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties (BZK)) has called mayors of the Dutch municipalities to make an inventory of their medium- to high rise buildings. A “BZK risk tool” was developed by DGMR, in collaboration with Nieman Raadgevende Ingenieurs and Hamerlinck Adviesbureau. It takes into account nine different aspects, categorized under facade characteristics and building characteristics. Facade characteristics are the use of combustible materials in the outer facade layer (in vol.%), the use of combustible materials of in the layers adjacent to a (ventilated) cavity (in vol.%) and for both whether risk reducing measures are implemented (e.g. interrupting the outermost layer and placement of cavity barriers). The building characteristics evaluated in the BZK risk tool are the function, the height, the amount of escape routes, risk reducing measures along these escape routes (e.g. no facade openings) and additional provisions regarding fire safety. Every aspect of the facade- and building characteristics is graded with a number, a total score is calculated by taking the product of all scores. These scores determine the risk category: green (low risk), yellow (medium risk), orange (high risk) or red (severe risk).

The full setup of the BZK risk tool is found in Appendix A. It should be noted that the tool is designed as a quick scan of the fire safety of a building, as the input is very limited. This lack of detailing in the input makes that the outcome does not offer a solid foundation for conclusions. Therefore, if a building is categorized in the BZK risk tool as orange or red, additional investigation is required to determine the actual risks.

2.2 Relevance

The regulations and the risk assessment on the fire safety of facades have been discussed, the practice and the relevance not yet. A list of incidents, showing the relevance of the subject, is found in Table 1. In all these events, the facade played an important role in the spread of fire to adjacent fire compartments. Different building characteristics are considered: the construction period, the amount of floors, the function of the building (mostly residential) and facade construction. Also, the cause of the fire is considered to have a list of potential threats.

Table 1: Summary of facade fires since 2012

Year	Tower (Location)	Construction	Floors	Function	Facade construction	Source of fire
2012	Al Tayer Tower [15] (Sharjah, UAE)		40	Residential	ACM	Cigarette butt on a balcony on the 1st floor
2012	Mermoz Tower [16] (Roubaix, France)		18	Residential	ACM with a PE core	On a balcony on the 1st floor
2012	Tamweel Tower [17] (UAE)		34	Residential	ACM	Discarded cigarette
2014	Lacrosse Tower [18], [19] (Melbourne, Australia)		23	Residential	ACM	Discarded cigarette
2015	Marina Torch (Dubai, UAE)	2005-2011	80	Residential	ACM with a PE core	Unknown source
2016	Address Downtown [20][21] (Dubai, UAE)	2005-2008	63	Hotel Residential	ACM	Electrical short circuit on a ledge between the 14th and 15th floor
2016	Ramat Gan [22] (Rabat Gan, Israel)		13	Residential	ACM with a PE core	Unknown source
2016	Neo Soho (Jakarta, Indonesia)	Under construction			ACM with a PE core	Unknown source
2016	Shepherd's Court [23] (London, UK)		18	Residential	Panels consisting of a plywood board, a PE core, steel sheet and decorative paint	Faulty tumble dryer on the 7th floor
2016	Sulafa Tower [24], [25] (Dubai, UAE)	2006-2010	75	Residential	ACM with a PE core	Discarded cigarette inside an apartment on the 61st floor
2017	Grenfell Tower (London, UK)	1972-1974 *Renovation 2012-2016*	24	Residential	ACM with a PE core, resol insulation	Malfunctioning fridge-freezer on the 4th floor
2017	Marina Torch [26], [27] (Dubai, UAE)	2005-2011 *Renovation 2016*	79	Residential	ACM with a PE core	Discarded cigarette
2019	Neo 200 [28] (Melbourne, Australia)	2005-2007	41	Residential	ACM	Discarded cigarette
2019	Cube [29] (Bolton, UK)	*Re-clad 2018*	7	Residential	HPL	Discarded cigarette
2020	Abbco Tower [30], [31] (Sharjah, UAE)	2005-2008	49	Residential	ACM	Cigarette butt or shisha coals on a balcony on the 10th floor
2021	Torre del Moro [9] (Milan, Italy)	2009	18	Residential	ACM with a PE core	Electrical short circuit on the 15th floor

Already mentioned and possibly the most infamous example in the list of incidents, is the fire in the Grenfell Tower in London. During its renovation, the facade was re-clad with aluminum composite material (ACM) panels, with a cavity and an EPS insulation layer behind these panels. The fire was able to break out via three routes: via the combustible insulation core panel that housed the ventilation fan for the kitchen, via an open window and via broken glazing (failure of the daylight openings) [32]. After this breakout, the facade construction itself combusted, and allowed fast spreading in all directions: first towards the roof and from there, the fire spread horizontally and downwards via melting facade material [1].

When the fire was discovered and the fire brigade alarmed, the fire brigade imposed a “Stay-put”-order. “Stay-put” is the standard evacuation strategy in the United Kingdom for residential buildings, meaning that residents must stay in their apartments until the fire brigade arrives and can conduct the evacuation. This is done to ensure safe evacuation of the occupants, but the scenario of the fire penetrating into other apartments via the facade was not taken into account. This highlights the importance of discrete facade design: a “Stay-put”-order can be considered as a safe evacuation strategy when a flanking fire cannot penetrate into adjacent fire compartments.

Facade materialization

As briefly mentioned before, thermally thin facades are not necessarily fire safe, even if they have been tested to comply with the Dutch Building Code. All aforementioned events where fire spread took place via the facades, have in common the application of thermally thin facades. It can be assumed that failure of the facade was never intentional, nevertheless the facades contributed to severe spreading of fire via the facade construction. External flames have shown to easily ignite combustible facade materials, causing shortcutting of the fire compartmentation.

Observing the list of events, remarkable is the amount of times ACM panels have been involved in flanking fires. ACM panels are sandwich panels consisting of two thin layers of aluminum, often filled with a hard plastic layer in between. Generally, this hard plastic layer within the sandwich panel is either polyethylene (PE) or fire retardant polyethylene (FRPE) [33]. The advantages of using ACM panels in facade design are the design flexibility they offer, the easy installation of the panels and the fact that the panels are maintenance free [34]. However, due to the low melting temperature of aluminum, and especially when applied in their execution with a combustible PE-core, they are nonresistant against a facade fire. Additionally, these types of facade panels are often applied in combination with combustible insulation materials and always applied with a ventilated cavity to avoid moisture problems. However, this feature offers another route for heat transfer via convection, and as mentioned before, flames can spread up to 10 times as high as they otherwise would due to the chimney effect. An 3D impression of the application of Reynobond ACM panels is shown in Figure 2, retrieved from the Grenfell Inquiry [1], [35].

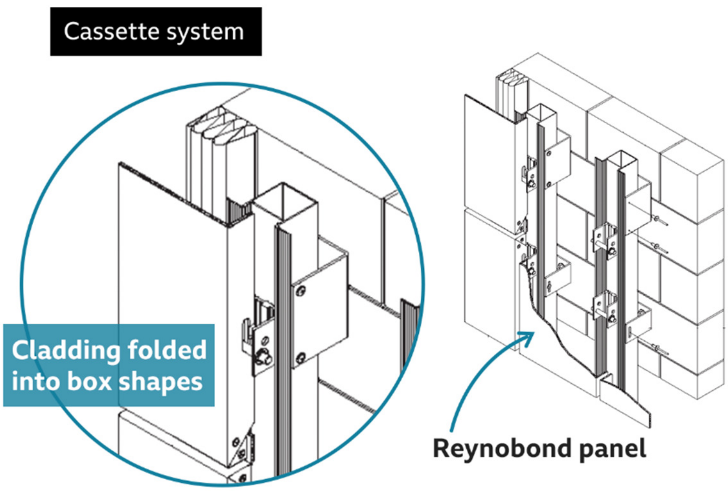


Figure 2. 3D impression of the ACM cladding of the Grenfell tower [35]

Once the external flame had broken out of the apartment where the Grenfell fire had started, many other characteristics of the renovated Grenfell facade played an important role in the disastrous fire spread; not just the cladding material. The cavities behind the ACM panels were provided with horizontal cavity barriers on each floor, indicated with green in the Grenfell facade detail in Figure 3. Additionally, vertical cavity barriers were applied to prevent horizontal fire spread. However, these cavity barriers were not applied in an adequate manner, allowing fire to spread both vertically and horizontally around these barriers [36]. In addition, the PIR insulation behind the cavity conforms to fire class C, implying that the material is flammable. Applied behind ACM panels with fire class E (highly flammable), implied that both these top layers acted as fuel to the fire.

However, as there is less information available on the other incidents than there is information available on the Grenfell fire, the focus will mainly be on the thermally thin cladding materials, assuming to be applied with a (ventilated) cavity or directly onto a flammable insulation layer. Thermally thin cladding materials are cladding materials that offer very little thermal mass. ACM panels are an example of thermally thin cladding materials; other thermally thin cladding materials are high-pressure laminate (HPL) cladding and brick slips, directly attached onto a plastic insulation layer. Especially the latter becomes increasingly popular in the Netherlands, because of the traditional brick appearance. Brick slips are lightweight, easy to apply and can be combined with different types of insulation [37]. The material conforms to fire class A, because the material is non-combustible [38]. However, research has shown that masonry typically is not completely resistant: spalling or deformations may occur when the material is exposed to fire [39], [40].

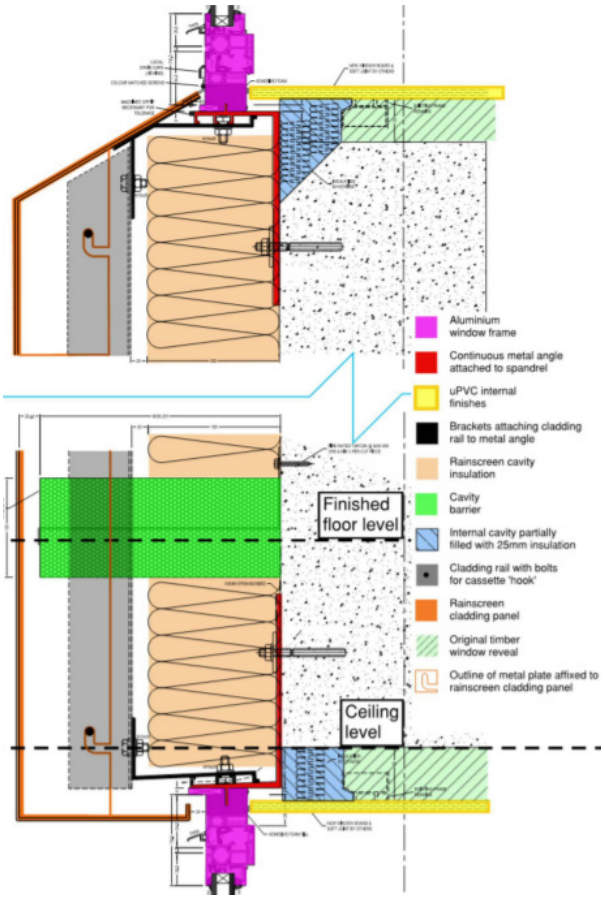


Figure 3. Detailing of the installation of the Reynobond ACM panels of the Grenfell tower [36]

Fire behavior in cavities

(Ventilated) cavities in facade systems come with advantages and disadvantages. They are often applied as they eliminate condensation on the inside of the facade wall and contribute to thermal comfort and energy saving [41], both in traditional (Dutch) brickwork houses and in newer facade systems, such as thermally thin facades. A disadvantages occurs in the event of fire, as (ventilated) cavities offer an extra route of fire spread. As mentioned before, flames may reach up to 5 to 10 times higher in a cavity due to chimney effect.

Three different aspect should be understood regarding fire propagation in cavities:

1. **How the fire can enter a cavity.**

Fires are able to enter a cavity when no adequate fire barriers are installed at critical areas, i.e. around window and/or door frames [42] or when (part of) the facade breaks down under critical exposure to the high temperatures.

One example where fire was able to penetrate the cavity as a result of dissatisfactory fire barriers, was during the Grenfell fire. Different routes were distinguished from where the fire could enter the cavity. The first route via faulty connections between the window frames and the facade (see Figure 3 for an example); secondly via faulty connections between the window frames and the columns along the facade (see Figure 4 for an example); thirdly via an open or a broken window; and lastly via the ventilation fan [32]. Fire spread into the cavity first happened via the faulty connection between the window frames and the columns along the facade, most likely due to a lack of adequate fire barriers.

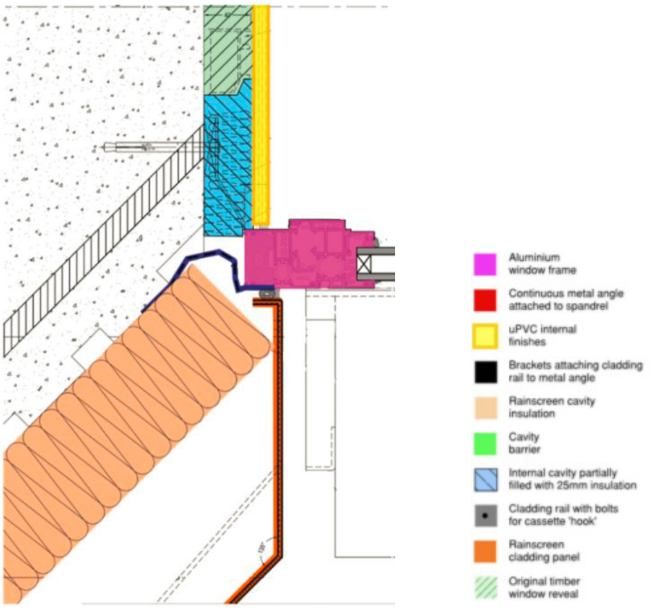


Figure 4. Detailing of the Reynobond ACM panels used on the Grenfell tower (plan view) [36]

2. **How the fire propagates through the cavity.**

Mentioned before is how the chimney effect significantly increases fire propagation through a cavity. The chimney effect can be defined as the airflow through the cavity, caused by the pressure difference between lower and higher parts of the cavity [41]. In the event of fire, these pressure differences are increased significantly, hence the increased flame height. The flame height inside a cavity is dependent on the cavity width: experimental research has shown that the flame height increases with decreasing cavity width [43]. This was later also found in numerical analysis: simulations done in Fire Dynamics Simulator (FDS) showed a higher flame height in the set up for cavities with a lower cavity width [44].

To restrict the flame height in cavities, cavity barriers and/or fire stops can be applied. While these two terms are often used interchangeably, a distinction between the two interventions can be made. The difference here is the materialization of the interventions, and therefore also the way they function [45]. Cavity barriers are made of fire-resistant material, e.g. mineral fiber slabs [46], [47]. These barriers close off passage through the cavity at all times, what implies that cavity ventilation is cut off completely.

If ventilation through the cavity is needed, fire stops can be applied in the cavity. Fire stops are made from intumescent materials. These materials expand when they are exposed to high temperatures, creating a protective seal [45]. Innovative designs have been developed in order to fit a wide range of projects [48], [49]. One (patented) example of a fire stop is shown in Figure 5, which clearly demonstrates the behavior of the intumescent material in the event of cavity fire.

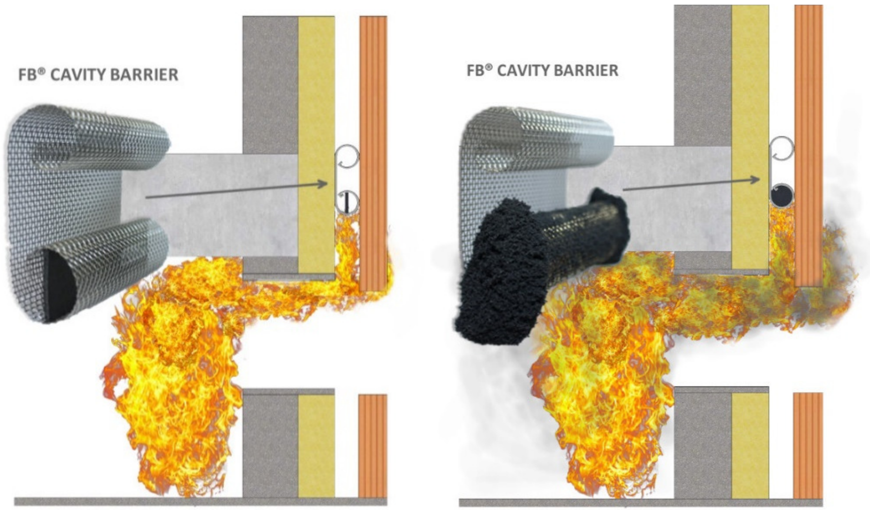


Figure 5. Fire stop developed by Odice Passive Fire Protection [48]

The most important function of both cavity barriers and fire stops is to prevent fire propagation via the cavity. The risk of fire propagation is highest in the vertical direction, due to the chimney effect. Consequently, most multi-story buildings have cavity barriers or fire stops running in horizontal direction. Horizontal cavity barriers and fire stops are often applied at every floor, to prevent fire spread to overhead compartments. In order to prevent fire spread in the horizontal direction, cavity barriers can also be applied in vertical direction.

It is critical that cavity barriers and fire stops are installed adequately. It has been mentioned before that the cavity barriers applied in facade construction the Grenfell tower were not installed properly, leaving gaps and crevices (example given in Figure 6) [11]. This offered a direct route of fire propagation through the cavity during the Grenfell fire in 2017. Other failures of the cavity barriers/fire stops of the Grenfell tower included early fire propagation around the intumescent strips of the fire stops (thus before it was activated and started expansion), afterwards via a route around the expanded fire stop due to distortion of the ACM panels and via the combustible PE core of the ACM panels [11]. It has also been shown in research that cavity barriers may not be as reliable as designed for. Čolić & Pečur [50] tested the effectiveness of horizontal and vertical cavity barriers in a facade system with non-combustible ACM cladding. For all test setups, the vertical cavity barriers passed the fire test of 60 minutes, meaning that fire spread in horizontal direction was sufficiently prevented. The horizontal cavity barriers only passed the tests when sufficient barriers were installed (vertical distance approximately < 2.60 m) [50].

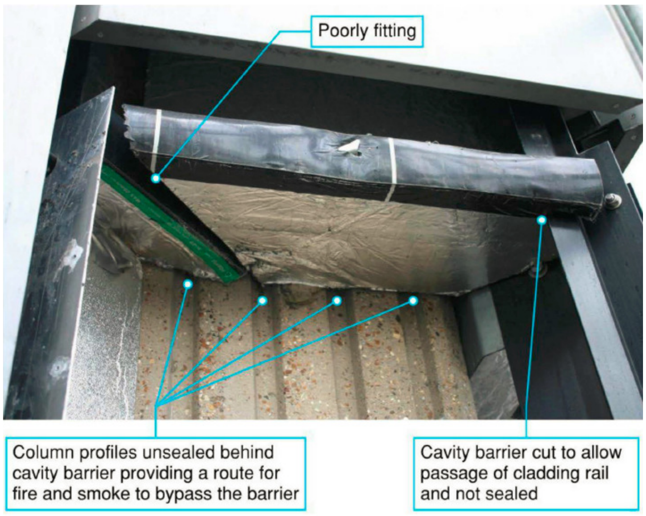


Figure 6. One cavity barrier as applied in the facade construction of the Grenfell tower [11]

Of course, fire spread is only possible through cavities for as long as the outer layer of the facade stays in tact. If the outer layer falls out (or even combusts), and the insulation layer applied is made from a combustible material, the fire will develop as a facade fire rather than a cavity fire.

3. **How a fire in the cavity threatens other fire compartments.**

Cavity fires penetrate fire compartments in the same manner as they were able to break out of the original compartment: often due to poor detailing. Critical areas are again around facade openings, such as windows. Use of combustible materials around these openings, or non-combustible materials with a low melting point, increases the risk of fire spread back into the building.

This was also the case for the Grenfell tower, where fire had easy access into other compartments via similar routes as from where it could break out in the first instance. Witnesses mentioned melting materials around the window openings; falling out of the ventilation fan into one of the apartments, allowing smoke and fire to spread into the apartment; and fire penetrating an apartment via the connection of the window frames and the facade. These statements can be found in the report by Dr. Lane (Section 9) [32].

3. Research objective

The fact that thermally thin facades are often involved in flanking fires, highlights the importance of thorough facade design. The aim of this research is to gain insight on how thermally thin cladding materials affect the risk of facade fires, via conduction, convection, radiation and combustion, even if the cladding material itself is non-combustible. The outcome of the project will be in the form of design recommendations regarding materialization and building technology.

To come to these insights, conclusions and design recommendations, a case study is performed on “De Ananas”. De Ananas is an apartment complex under construction and is located in Leiden, the Netherlands. One of the apartments is simulated in OZone to test whether an apartment fire would result in an external flame and consequently threatens the facade construction. Assuming that an external flame would indeed occur in the event of fire, the cladding is tested with a COMSOL Multiphysics model for conduction: how fast the external flame would heat up the cladding layer completely to form a threat for the underlying insulation layer. This COMSOL Multiphysics model is then used to test other types of thermally thin facades.

4. Case study on "De Ananas"

4.1 Introduction

"De Ananas" in Leiden is a residential complex under construction. When completely finished, the complex will consist of 19 different segments with varying heights: from 8 floors up to the 19 floors. A schematic overview of all segments can be found in Figure 7 [51].

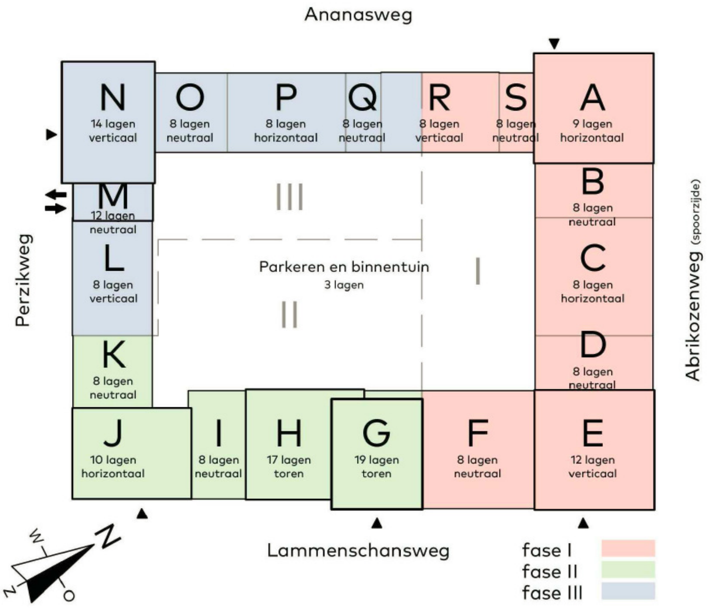


Figure 7. Schematic plan of the "De Ananas"-complex with segments A to S indicated [51]

An impression of the "De Ananas"-complex will look like can be found in Figure 8 [52]. Apart from the varying heights of the segments, the diverse colors of the facade also provide a sense of a partition in different segments.

Figure 8. Elevation of the complex, as seen from the Ananasweg [52]

In all segments, the main function is living. All dwellings on the ground floor are so-called maisonettes, meaning that they have a second floor. The dwellings from the second floor onwards are single floor apartments of various sizes. A floorplan showing the distribution of these apartment is found in Appendix B [53].

Two levels of parking, storage spaces and bike parking spaces are hidden beneath a courtyard, which is thus elevated to the third floor. To clarify, a section of the complex is shown in Figure 9 [52]. This courtyard offers an outdoor space for relaxing and recreation for the residents of "De Ananas". The parking can be accessed via the entrance in segment M, the courtyard can be accessed via the porches located in segments A, J and N. Technical spaces for the building services are found in segments B, C and D.

Figure 9. Section of the "De Ananas"-complex with an elevation on the segments along the Lammenschansweg [52]

An elaborate analysis on "De Ananas" regarding the fire safety aspects is discussed in the next section.

4.2 Fire safety analysis

Internal construction

From the retrieved plans and sections, it is concluded that the internal wall- and floor structure is load-bearing. This structure is generally based on a grid with 7200 mm between loadbearing elements, the loadbearing elements being concrete walls with a thickness of 250 mm. In segments G, H and I, the distance between the load bearing elements is 5400 mm. The floors generally span in one direction, from one concrete wall to the other.

Concrete (loadbearing) walls have favorable properties regarding fire safety: the fire resistance of concrete is high and the material itself is non-combustible. It does not contribute to the fire load and does not produce smoke or toxic gases when exposed to fire [54]. According to the Dutch Building Code, loadbearing walls should withstand fire for 120 minutes for buildings where the highest floor is 13 m above ground level. Concrete walls with a thickness of 120 mm conform to this requirement [55], [56], and it can therefore be concluded that the loadbearing elements of "De Ananas" satisfy [56].

Non-loadbearing walls that function as a separation wall between different apartments, are metal stud walls with two layers of Gyproc panels and a double layer of mineral wool (2x 75 mm) in the cavity. With decent application, these walls satisfy for a WBDBO of 60 minutes and are indicated. The walls that separate the apartments from the corridors are similar metal stud walls, mainly to also ensure sufficient sound insulation between the apartments and the corridors. These walls satisfy for a WBDBO of 30 minutes [56].

An overview of the different wall types can be found in Figure 10 [56]. This floor plan shows segments E, F and G. The floorplan for all segments is added in Appendix C. The walls with a WBDBO of 60 minutes are indicated in green; the walls with a WBDBO of 30 minutes are indicated in orange. This construction ensures that every apartment is a separate fire compartment.

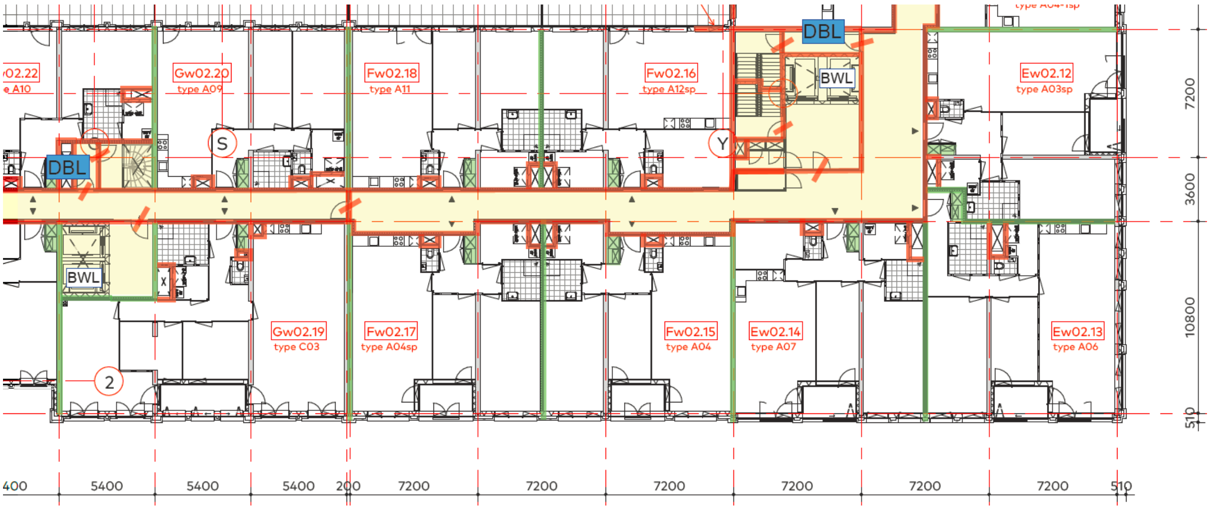


Figure 10. Floor plan of segments E, F and G, fire (sub) compartments indicated [56]

Facade construction

The exterior walls are non-loadbearing and thermally thin. From studying the provided detailing of the complex that the facades are either consisting of a timber frame construction filled with mineral wool (thickness either 235mm or 155mm), a cementitious board (thickness 15mm), an EPS insulation layer (thickness either 200mm or 140mm), finished off with brick slips as produced by Strikolith (thickness 4mm) or the aluminum "De Ananas" profile (thickness 2mm). One detail and a 3D-impression of the Strikolith Flex system are found in Figure 11 [51], [57]. Other segments are provided with special "De Ananas detailing", architectural details made from aluminum. A detail and impression of this detailing can be found in Figure 12.

The facade openings on all levels spread from the floor to almost the ceiling in all apartments. This is also the case for the glazing in front of the loggias.

As the facade construction is thermally thin, it is expected that there is a significant risk of failure of the facade in the event of a fire occurring in the complex. This as the thermal load of an external flame could soften the EPS; this will happen for temperatures above 100 °C [58]. The softening of the EPS could lead to cracks in the cementitious layer and eventually ignite the EPS layer through these cracks. Research has shown that the cementitious layer itself will also lose its strength significantly when exposed to temperatures higher than 400 °C [59]. This causes cracking of the cementitious layer and parts of the facade construction falling out [60], again exposing the combustible EPS layer.

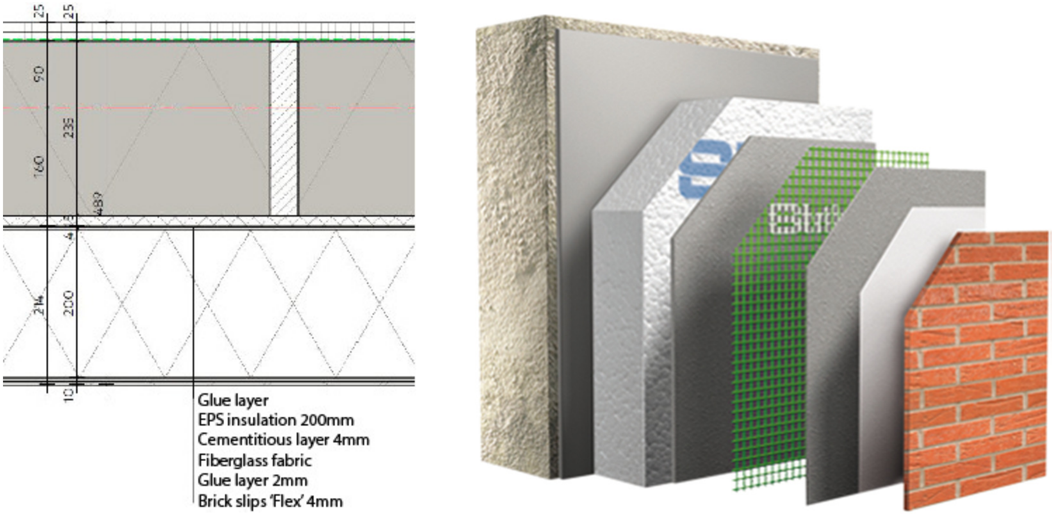


Figure 11. Detail (01.05) [51] and 3D-impression of the Strikolith "steenstrips Flex" (not on scale) [57]

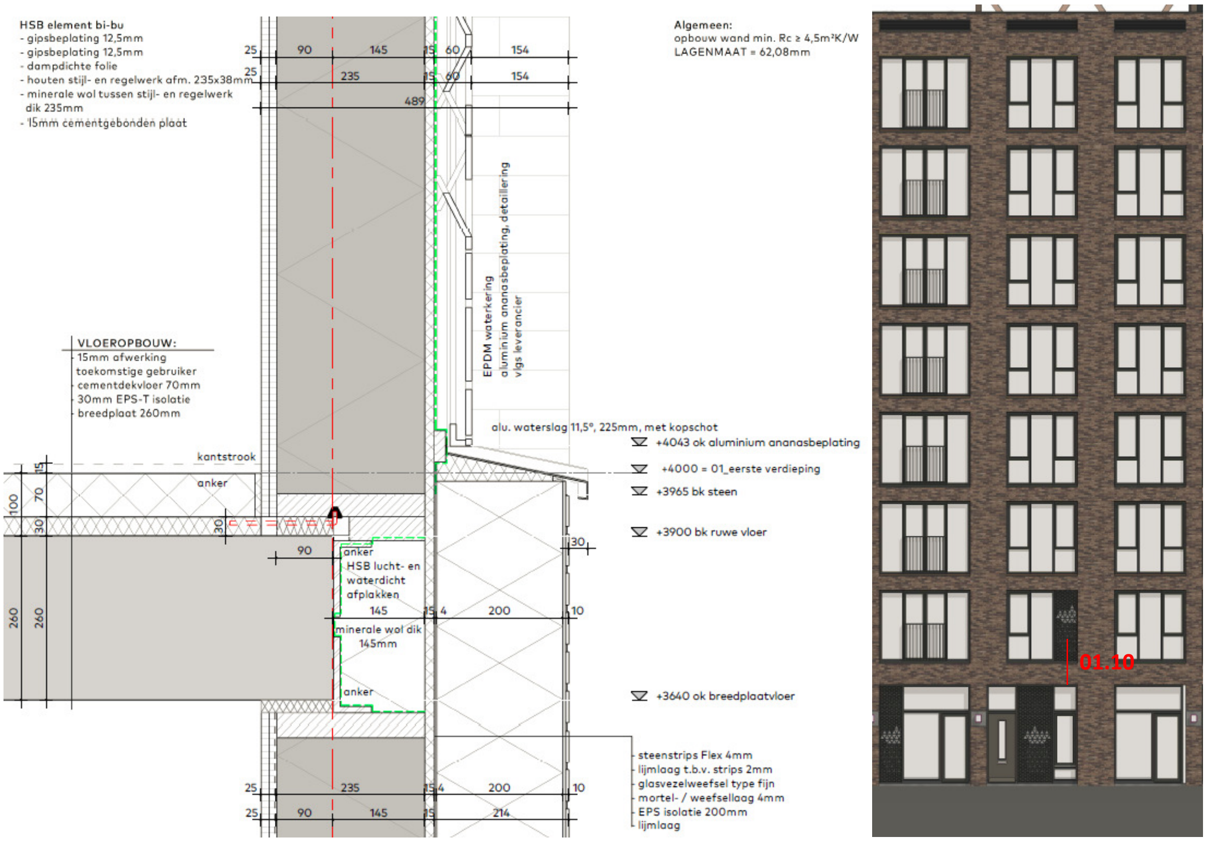


Figure 12. Detail (01.10) [51] and elevation with the detail indicated [52]

Accessability and escape routes

The dwellings on the ground floor have their entrance along the Ananasweg, the Perzikweg and the Lammenschansweg. The apartments from the second floor onwards are accessed either indoor or outdoor corridors. In apartments in the segments along the Lammenschansweg and the Abrikozenweg can be reached via an indoor corridor. The apartments in the segments along the Ananasweg and Perzikweg are reached via an outdoor corridor. Exceptions are the apartments on the second floor in segments K up until S, the apartments can be accessed via the courtyard.

The porches for the apartments are located in segments A, E, G, J and N and are indicated in Figure 7 with an arrow. Here, the elevators are found and two extra protected escape routes ((emergency) stairs). The corridors leading towards these stairs are also designed as extra protected escape routes and never go through any fire compartments; this can also be retrieved from the fire safety overview in Figure 10 [56].

"De Ananas" and the BZK risk tool

Introduced was also the BZK risk tool, developed for the Dutch Ministry of the Interior and Kingdom Relations. As mentioned, this tool is developed to enable quick evaluation of medium- to high rise buildings regarding their fire safety, and categorization of these buildings in four risk categories: green, yellow, orange and red.

This is also done four five different segments of "De Ananas". The facade characteristics are the same for all segments: a vol.% > 30% of flammable material is considered. This is calculated by examining the outer 20 mm. The Strikolith facade system has a total thickness of 10 mm, which implies that also 10 mm of EPS is included in the calculation, resulting in 50 vol.% of flammable materials in the outer layer. There are no risk-reducing measures implemented, and no cavity needs to be taken into account.

However, there is some distinction to be made in the building characteristics of the different segments. These segments vary in amount of floors, the full height of the building and the distance to the nearest emergency staircases [53], [61]. These characteristics are listed in Table 2.

Table 2. Building characteristics as input for the BZK risk tool

	Floors (incl. ground floor)	Height of the highest floor [m]	Location of emergency staircases
Segment A	9	24.86	Two staircases in separate cores, located in segment A
Segment F	8	21.88	Two staircases in separate cores, located in segment E + two spiral staircases in one core, located in segment G
Segment G	19	54.66	Two spiral staircases in one core, located in segment G
Segment F	17	48.70	Two spiral staircases in one core, located in segment G
Segment N	14	39.76	Two staircases in separate cores, located in segment N
Segment S	8	21.88	Two staircases in separate cores, located in segment A + two staircases in separate cores, located in segment N (distance approximately 72 m via an outdoor corridor)

From the analysis of "De Ananas" with the BZK risk tool, it was taken that all segments of the complex will be categorized as at least yellow, thus form a medium risk in the event of fire. This is a combination of the applied Strikolith facade construction (increasing the risk induced by a fire by a factor 16) and the residential function of the complex (increasing the risk induced by a fire by a factor 4). The only active fire fighting measure found is in the form of the availability of a dry pipe, intended to support the fire brigade. No other active measures such as sprinklers are present in the different segments. As it is uncertain how well the facade performs in the event of fire, also no passive fire resisting provisions are considered for the complex. The limited height of most segments (< 40 m) and the easily reachable emergency staircases make sure that most segments can be categorized as yellow.

Segments G and H are the only segments in another category, namely the red category (severe risk). They score much higher compared to the other segments, as the height of the top floors of these segments is at 54.66 m and 48.70 m, respectively. This different height class increases the risk induced by a fire by a factor 2, compared to all other segments with a height below 40 m. In the event of a fire (or another emergency), the only way to evacuate is via the spiral staircases located in segment G. It could be questioned why one would choose for this type of staircase for the highest two segments, as this increases the risk induced by a fire by a factor 2. Again, no additional active or passive fire fighting or fire resisting provisions are considered, resulting in a classification in the red category.

4.3 OZone simulation

One of the apartments of the "De Ananas"-complex is studied in OZone to simulate what happens in case of compartment fire inside one of the apartments. The OZone simulation model is based on a natural fire concept, according to NEN 6055. In a natural fire concept, both fire characteristics and building characteristics are taken into account. A natural fire concept is a more realistic alternative for the standard fire curve.

In the different segments of "De Ananas", apartments of different sizes can be found. The selected apartment is an average sized apartment, from the type A04. The apartments of type A04 (and type A04sp) are found in the segments B, D and F. The floorplan of two of these apartments is found in Figure 13 [53]. These apartments (Fw02.15 and Fw02.17) are located segment F. Apart from being mirrored, the two apartments are identical. One of these two apartments is modelled in OZone (version 3.0.4). The main objective of Ozone is to predict the natural fire in both pre-flashover and post-flashover situation. When post-flashover, the fire is oxygen controlled, external flaming will occur through the openings of the compartment. External flames will be more severe when the lack of oxygen increases. The OZone model is used to foresee whether a fire in the apartment will cause an external flame, the rate of heat release of this external flame and the duration of the external flame. The results are then used to assess the threat that this fire will have on the facade.

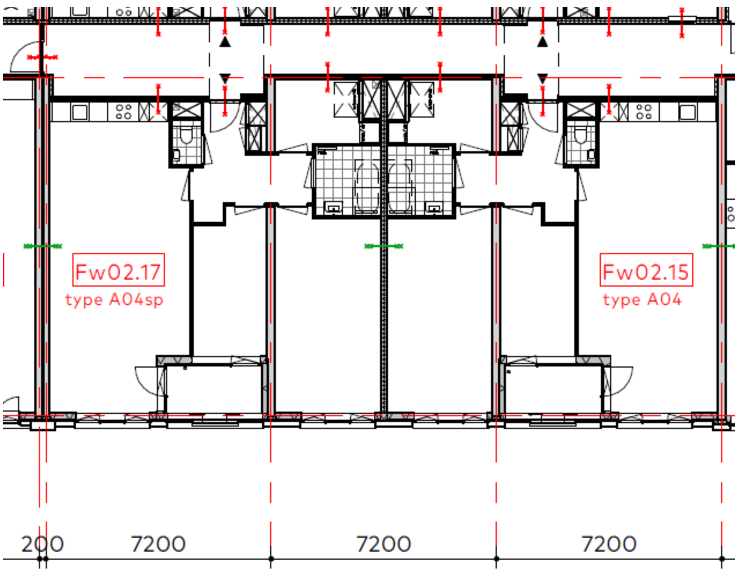


Figure 13. Floor plan of the simulated apartment [53]

In OZone, the compartment properties and the fire properties need to be defined. Apartments of type A04 are 10.8 m in width, 10.8 m in depth and 2.62 m in height. In Table 3, the other compartment properties as set in OZone are listed. The floor and the ceiling consist of a normal weight concrete floor, EPS-T insulation and a cement top layer. Wall 1, Wall 2 and Wall 3 are representing the interior walls. As the interior walls prevent fire spread towards other compartments for at least 60 minutes, the construction of the three interior walls is simplified as a single layer of normal weight concrete with a thickness of 250 mm. Wall 4 represents the facade. As only four layers can be modeled in OZone per construction element, it is chosen to only model the interior gypsum boards, the mineral wool insulation, the EPS insulation layer and the brick slip. The cementitious board of 15 mm is left out of consideration.

The definition of the daylight openings is found in Table 4. As OZone is a single zone simulation zone, the aforementioned loggias cannot be modeled in OZone. The loggia of the analyzed apartment is therefore put as one of the daylight openings (Opening 2 in Table 3).

Table 3. Material properties

Materials	Thickness	Unit mass	Conductivity	Specific Heat	Relative Emissivity	Relative Emissivity
	cm	kg/m³	W/mK	J/kgK	Hot surface	Cold surface
Floor / ceiling						
Cement top layer	7	1440	0,29	920	0,54	0,54
EPS-T insulation	3	50	0,03	1200	0,6	0,6
Normal weight concrete	26	2300	1,6	1000	0,8	0,8
Internal walls (Wall 1, Wall 2, Wall 3)						
Normal weight concrete	25	2300	1,6	1000	0,8	0,8
Facade (Wall 4)						
Gypsum board (2x)	2,5	900	0,25	1000	0,8	0,8
Glass wool	23,5	60	0,037	1030	0,8	0,8
EPS insulation	20	50	0,03	1200	0,6	0,6
Normal brick	0,4	1600	0,7	840	0,8	0,8

Table 4. Daylight openings

	Sill height	Soffit height	Width	Variation	Adiabatic
	m	m	m		
Opening 1	0,1	2,4	2300	Constant	no
Opening 2	0,1	2,4	3000	Constant	no
Opening 3	0,1	2,4	2300	Constant	no

The fire input is user defined and can be found in Table 5 [62]. The input data is based on the national annex to Eurocode 1 (NEN-EN 1991-1-2 / NA), for a natural fire concept. Important is that all multiplication factors (δ) under "Active Fire Fighting Measures" are 1; the physical zone model is used without risk factors.

Table 5. Fire properties

Compartment Fire	Annex E (EN 1991-1-2)	
National Annex	Default	
Occupancy	User defined	
Fire Growth Rate	300	-
RHRf	250	kW/m²
Fire Load qf,k	780	MJ/m²
Danger of Fire Activation	1	-
Max Fire Area	116,64	m²
Fire Elevation	1	m
Fuel Height	1,5	m
Fire Risk Area	12,5	m²
Combustion Efficiency Factor	0,8	-
Combustion Model	External flaming	
Stoichiometric Coefficient	1,27	-

Base scenario

From running the base scenario OZone, it was extracted that flashover occurs after 13 minutes. In Figure 14, the graph for the rate of heat release (RHR) and the Oxygen Mass are found. From the RHR-graph, it is concluded that a fully developed fire in one of these apartments would not result in an external flame, as all energy (in MW) is delivered within the compartment. As the oxygen mass is higher than 0 kg at all times, the fire remains fuel controlled, even after flash over.

The complete report for this simulation is found in Appendix E.

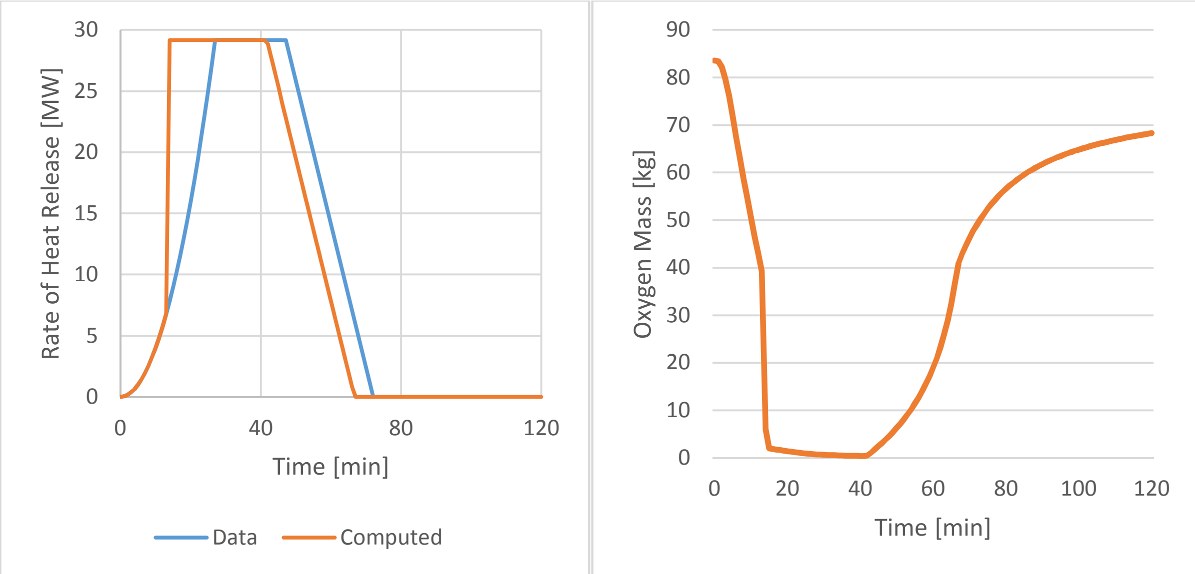


Figure 14. Results for the RHR and the oxygen mass of the base scenario

However, this scenario is purely theoretical. In reality, different factors may influence the outcome. A sensitivity analysis is performed to determine how different variables affect the outcome from the OZone model; whether or not a fire in one of the apartments results in an external flame. The same simulations are therefore done, but then:

1) a rate of heat release per unit area (RHRf) of 375 kW/m² instead of 250 kW/m²;
2) a fire load density of 900 MJ/m² instead of 780 MJ/m²;
3) a fire growth rate of 150 instead of 300;
4) failure of only daylight opening 1 and 2 (as set for the base scenario, see Table 4); and
5) failure of only daylight opening 2 (as set for the base scenario, see Table 4).

Scenario 1 – increased RHRf

The first adaptation to the base scenario is the assumption that the maximum rate of heat release per unit area of fire (RHRf) is 1.5 times higher than the RHRf of the base case. The RHRf, as described as 250 kW/m² in Table 5, is thus altered to 375 kW/m². All other facade- and fire characteristics remain as described in Table 3, Table 4 and Table 5.

According to the simulation results, flashover happens after 16 minutes. The resulting graphs for the RHR and the oxygen mass are plotted in Figure 15. From the computed Rate of Heat Release curve, it is concluded that not all energy is delivered within the compartment. The difference between the two graphs is approximately 13.2 MW (= 43.7 MW – 30.5 MW), implying that the power of the external flame is about 1.7 MW per meter. This is severely higher than the 30 kW the facade material was tested for and it can be questioned whether or not the brick slip cladding would sufficiently prevent flanking when an external flame occurs.

The complete report for this simulation is found in Appendix F.

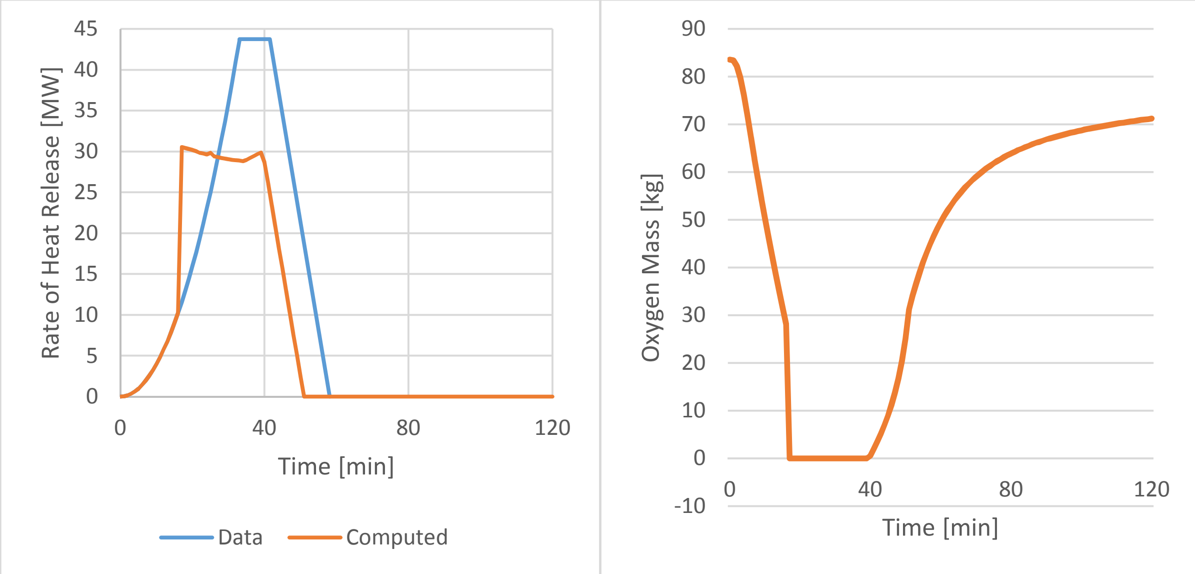


Figure 15. Results for the RHR and the oxygen mass of scenario 1

Scenario 2 – increased fire load density

In the base scenario, the input for the fire load density (qf,k) is 780 MJ/m². For dwellings, 780 MJ/m² is the average fire load density, which means that 50% of dwellings have a higher fire load density and 50% of dwellings have a lower fire load density. To see whether an increased fire load density results in an external flame, the input for the fire load density is increased to 900 MJ/m² for the third scenario. All other facade- and fire characteristics remain as described in Table 3, Table 4 and Table 5.

From running the third scenario in OZone, it is extracted that flashover occurs after 13 minutes. In Figure 16, the graph for the RHR and the Oxygen Mass are found. From the RHR-graph, it is concluded that a fully developed fire in one of these apartments does not result in an external flame. As the oxygen mass is higher than 0 kg at all times, the fire remains fuel controlled.

The complete report for this simulation is found in Appendix G.

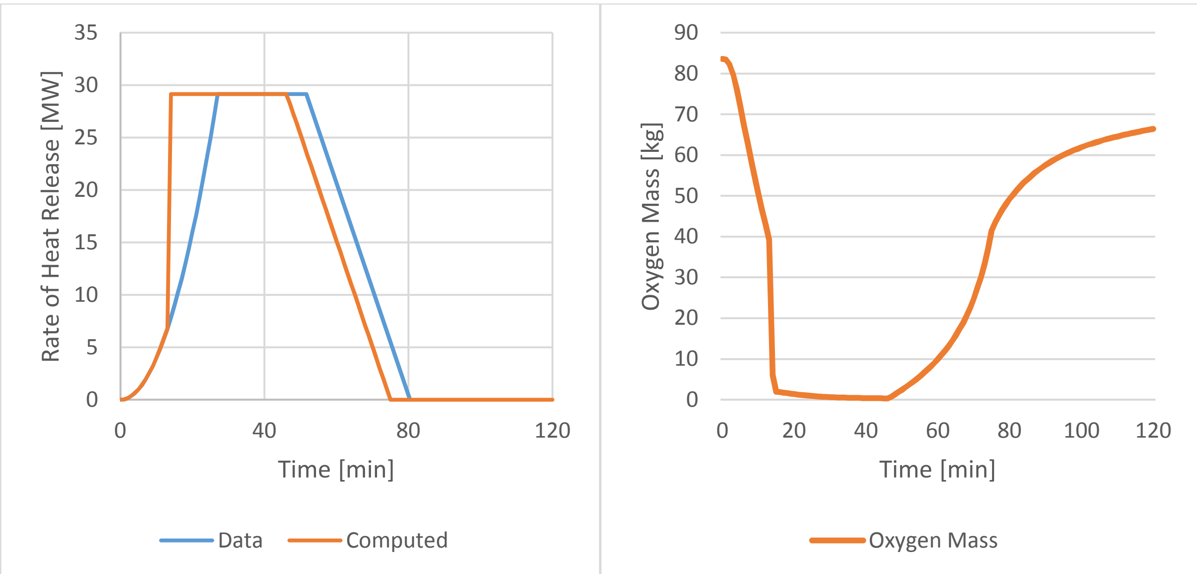


Figure 16. Results for the RHR and the oxygen mass of scenario 2

Scenario 3 – decreased fire growth rate

For scenario 3, the fire growth rate is halved from 300 to 150, which implies that the fire evolves twice as fast. All other facade- and fire characteristics remain as described in Table 3, Table 4 and Table 5.

From running this final scenario OZone, it was evident that the fire indeed evolves twice as fast, with flashover occurring at after 6 minutes. In Figure 17, the graph for the RHR and the Oxygen Mass are found and from the RHR-graph, it is concluded that a fully developed fire in one of these apartments would not result in an external flame. As the oxygen mass is higher than 0 kg at all times, the fire remains fuel controlled.

The complete report for this simulation is found in Appendix H.

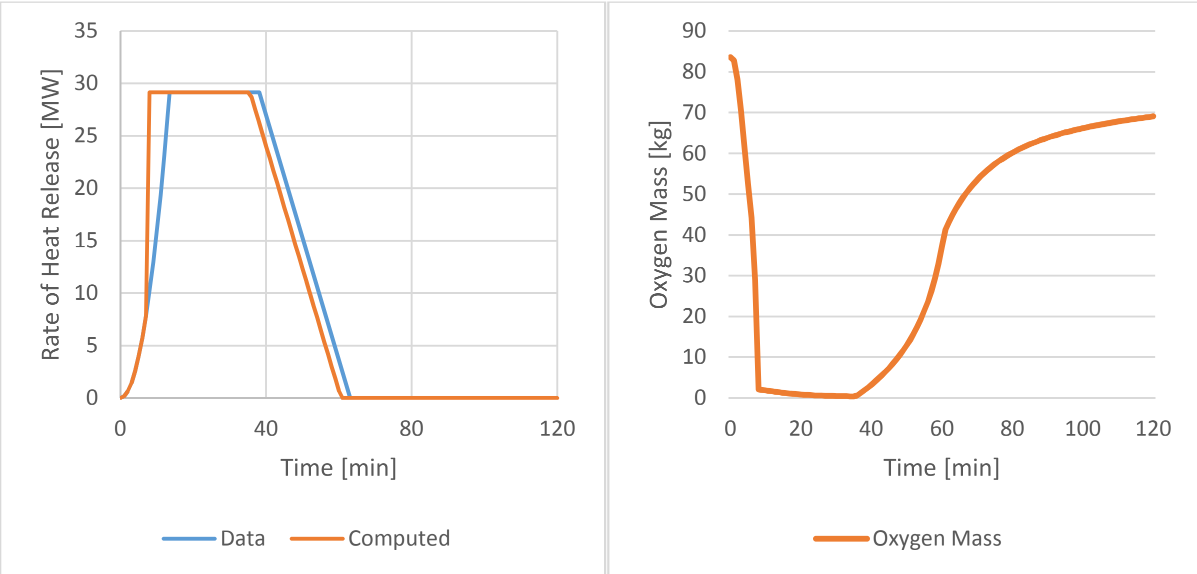


Figure 17. Results for the RHR and the oxygen mass of scenario 3

Scenario 4 – failure of two window openings

The fourth adaptation to the base scenario is the assumption that only two of the three window openings fail after flashover. Opening 3, as described in Table 4, is therefore eliminated from the simulation. All other facade- and fire characteristics remain as described in Table 3, Table 4 and Table 5.

According to the simulation results, flashover happens after 11 minutes. The resulting graphs for the RHR and the oxygen mass are plotted in Figure 18. From the computed RHR curve, it is concluded that not all energy is delivered within the compartment. This implies that the fire in the compartment results in an external flame, with a power of 8.7 MW (= 30.5 MW – 21.8 MW). The average power of the external flame along the facade would then be 1.6 MW/m. This is severely higher than the 30 kW the facade material was tested for.

The complete report for this simulation is found in Appendix I.

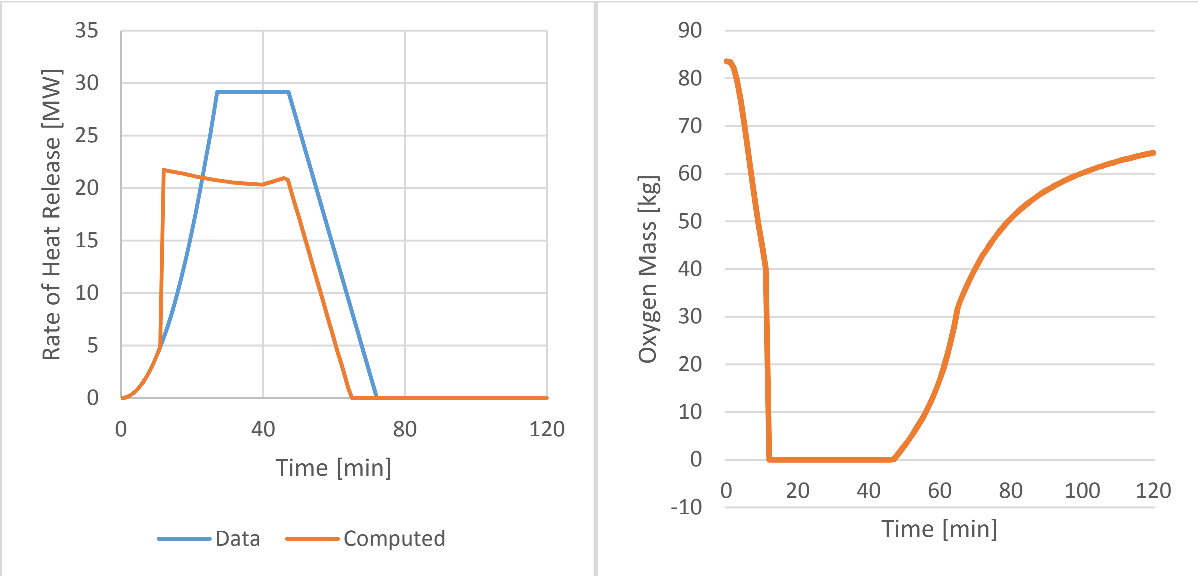


Figure 18. Results for the RHR and the oxygen mass of scenario 4

Scenario 5 – failure of one window opening

The last adaptation to the base scenario is the assumption that only two of the three window openings fail after flashover. Opening 3, as described in Table 4, is therefore eliminated from the simulation. All other facade- and fire characteristics remain as described in Table 3, Table 4 and Table 5.

According to the simulation results, flashover happens after 10 minutes. The resulting graphs for the RHR and the oxygen mass are plotted in Figure 19. From the computed RHR curve, it is concluded that not all energy is delivered within the compartment. This implies that the fire in the compartment results in an external flame, with a power of 18.3 MW (= 30.5 MW – 12.2 MW). The average power of the external flame along the facade would then be 6.1 MW/m. Again, this is severely higher than the 30 kW the facade material was tested for.

The complete report for this simulation is found in Appendix J.

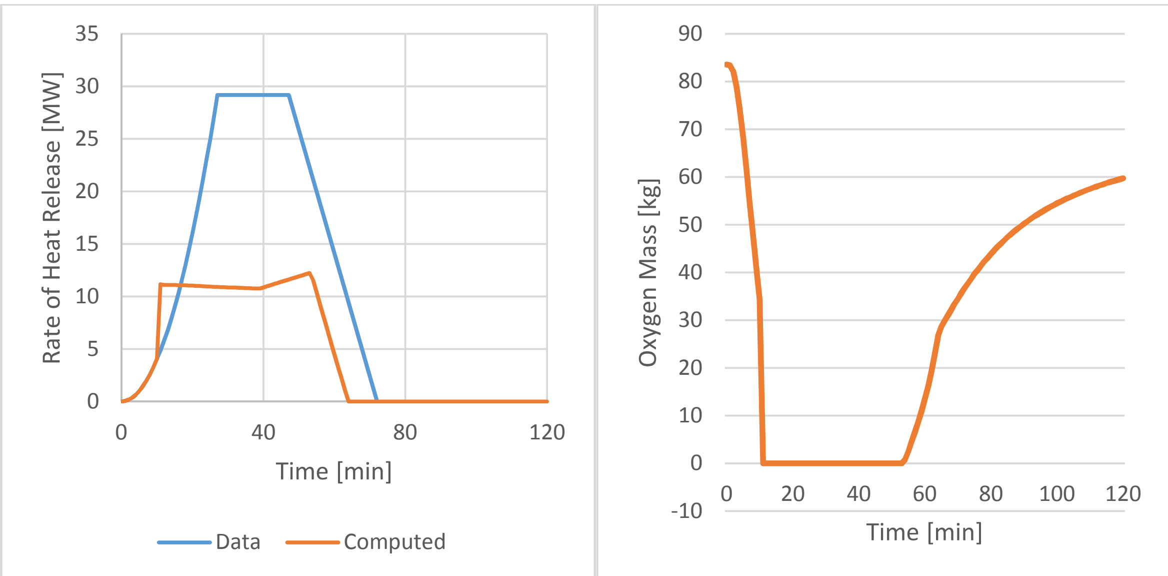


Figure 19. Results for the RHR and the oxygen mass of scenario 5

Probabilistic approach

Based on the sensitivity analysis, the risk probability is estimated using the probabilistic approach. Four different stochastic variables are considered, based on the different fire scenarios: the increase of the rate of heat release, the increase in fire load density, the time constant for fire development and the amount of window openings failing in the event of fire. As every stochastic variable can only occur once in this approach, scenario 5 (failure of only one window opening) is left out of consideration.

The calculated cumulative probability is plotted in Figure 20. On the x-axis, the rate of heat release of an external flame is plotted (RHR(ext)); on the y-axis, the cumulative probability is plotted (p(RST)). From this graph, it is retrieved that there is a 52.9% probability that no external flaming occurs (RHR(ext) = 0 MW). The facade system has been exposed to 30 kW during the SBI test; this is then multiplied by 7.6 m of window openings as it is assumed that 7.6 m of window openings would fail. This would then give a total RHR of 0.23 MW. The probability of an external flame occurring with an RHR higher than 0.23 MW is 46.5% and therefore significant. This shows that the testing of the materials for a fire with an RHR of 30 kW does not provide reliable results for a full size compartment fire happening, at least not for this specific case. The full calculation of the cumulative probability can be found in Appendix K.

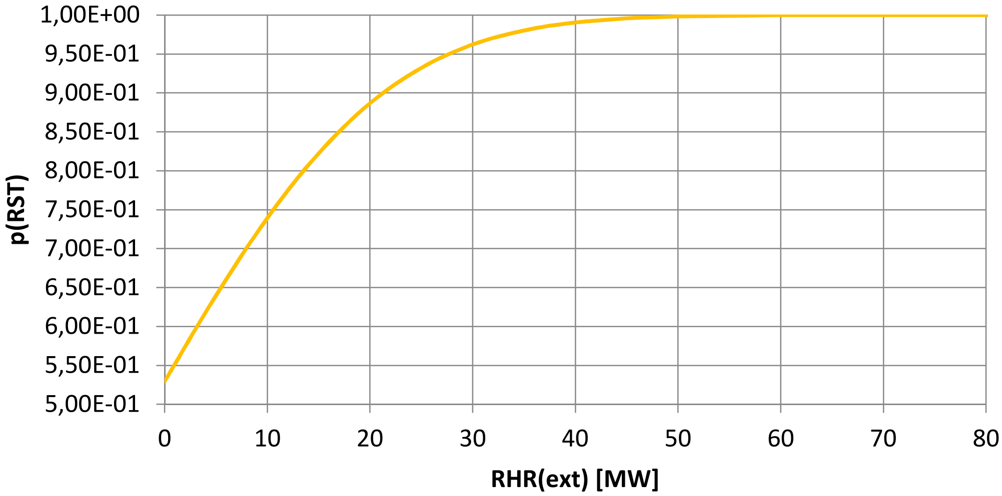


Figure 20. Cumulative probability

One other criterion for the reliability of facades in the event of an external flame is the amount of time that the facade is exposed to this external flame. The SBI test puts materials to test for only 20 minutes, while for all scenarios where an external flame occurs, the duration of this external flame exceeds 20 minutes. This shows again that the fire class determined by the SBI test does not satisfy for full size fires and external flames.

Limitations

During the process of modelling in OZone, certain limitations arose:

- Firstly, OZone is a single zone simulation program. It is therefore not possible to take into account interior walls inside a compartment. As each apartment is a separate fire compartment, the apartment is modelled as one zone, but this completely neglects the possible effect that interior walls may have on the development of the fire.
- Secondly, as OZone is a single zone simulation program, the loggias could not be included in the model. For this analysis, the loggia has been deemed a regular facade opening. It can be debated whether this is the correct method to deal with the loggia. However, from the past events where facades played an important role in the spreading of fire, the source of the fire was often exterior (e.g. a discarded cigarette), igniting possible fire loads stored on balconies. Residents of De Ananas may store combustible products in the loggia, and it is therefore chosen to include the loggia in the fire compartment.

- Lastly, the output of OZone consists of a limited amount of numerical results and graphs. Conclusions can be drawn from these graphs, but no visual result of the fire behavior is obtained with an OZone simulation.

4.4 COMSOL Multiphysics simulation

It is now established that a fire in one of the “De Ananas”-apartments has the potential to result in an external flame. As previously described, external flames threaten the facade in multiple ways. In the first place by ignition of facade layers. The brick slips that conform to fire class A prevent this from happening, as an external flame cannot reach flammable layers immediately (e.g. the EPS insulation layer). This has been concluded from studying the retrieved details [51], one of which is shown in Figure 11.

The second manner is via conduction, thus the heat transfer through the outer layer(s). Little heat can be accumulated in the brick slip and the cementitious layer, which implies that the underlying EPS insulation layer will heat up. This becomes problematic when the melting temperature (100 °C or 373.15 K) or even the temperature for (spontaneous) combustion (360 °C or 633.15 K) is reached [58]. To find out how fast the brick slip will transfer this amount of heat towards the EPS layer, the construction is modeled in COMSOL Multiphysics (version 5.6).

As the objective of this analysis is to find out how fast the brick slip will transfer the amount of heat needed for the combustion of the EPS layer, the 2D space dimension is selected under Model Wizard. The Physics used is heat transfer in solids (ht), as the construction consists of only solid materials. The chosen study is time dependent in order to be able to simulate changes that occur over time.

After setting up the model space, the actual model is build in the Model Builder. As this is a 2D-model and the desired outcome is data on one dimensional heat transfer, a section of only 1 m of facade is modeled. In Table 6, the model configurations are summarized. The geometry is shown in Figure 21, with from top to bottom the brick slip, the cementitious layer and the EPS layer.

Table 6. Model configurations for COMSOL Multiphysics

	Thickness [m]	Coordinates x	y	Density [kg/m³]	Heat capacity [J/kgK]	Thermal conductivity [W/mK]
EPS layer	0.200	0.000	0.000	11.5	1450	0.05
Cementitious layer	0.006	0.000	0.200	2247.4	980	2.79
Brick slip	0.004	0.000	0.206	2000	900	0.50

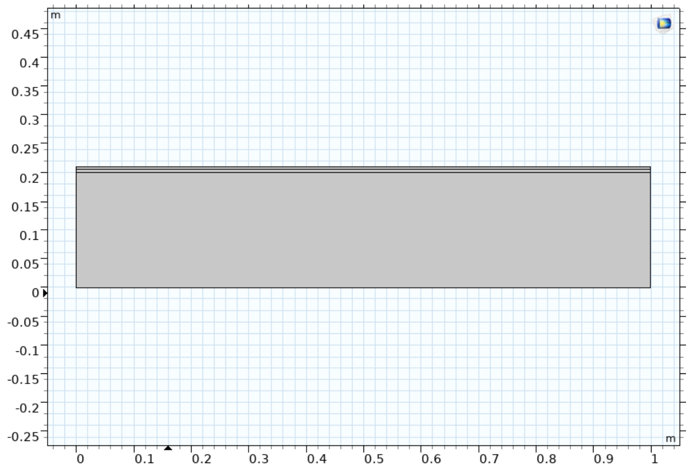


Figure 21. Geometry of the modelled “De Ananas”-facade

The initial temperature is 20 °C (= 293.15 K). At t = 0, the temperature at the exterior surface of the Strikolith layer is changed to 550 °C (= 823.15 K). 550 °C is the minimum temperature of an external flame, and t = 0 indicates the moment when the external flaming occurs. External flames have the ability to reach temperatures up to 1000 °C, with 550 °C as a lower limit [63], [64]. The temperature is highly dependent on the power of the external flame and varies along the height of the external flame. As the flame cannot be modeled in COMSOL Multiphysics, it is chosen to model for the lowest temperature.

The temperature at the cold side of the wall remains 20 °C (= 293.15 K) during the simulation. For the surfaces at both sides of the wall construction, convective heat flux is selected. The heat transfer coefficient applied is the external natural convection for vertical walls, with a length of 1 m. The pressure is kept constant at 1 Pa.

The simulations are run for 600 seconds, with a time step of 60 seconds.

The results are visualized in the plot in Figure 22. The arc length of 0.2 m indicates the where the Strikolith structure is applied onto the EPS insulation. Every curve in the plot indicates a different time, in a logical order. From the plot, it is observed that at t = 60, the EPS insulation is already heated by the heat transmission through the Strikolith structure.

The melting temperature of EPS, 373 K is reached after 9 minutes (t = 540 s). Melting of the EPS layer implies that the carrier of the Strikolith brick slips is lost. Consequently, the Strikolith construction may crack due to the lack of support and in that case, offer a direct route for the fire to ignite the EPS layer.

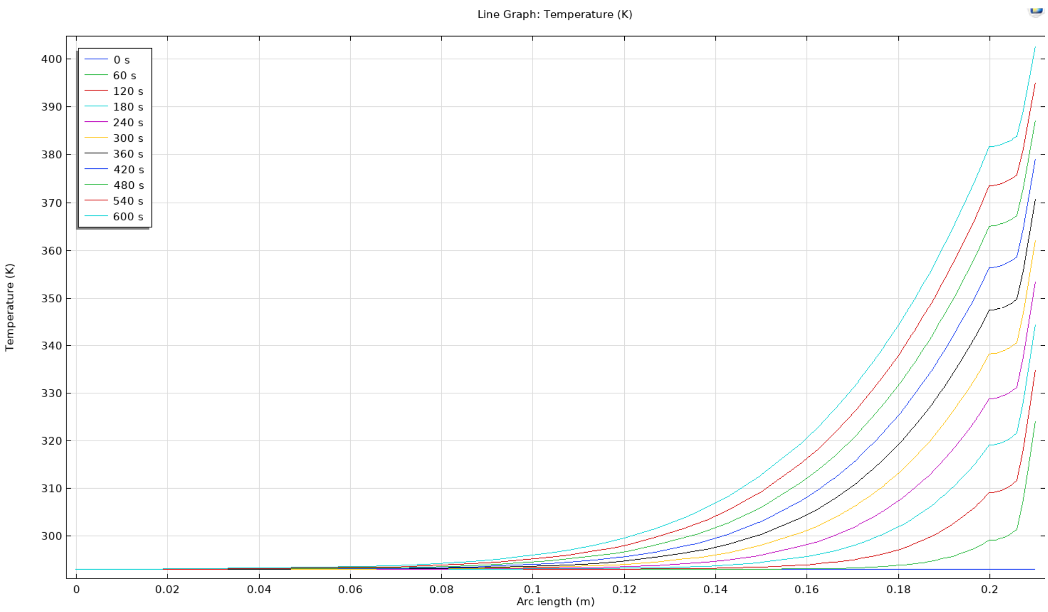


Figure 22. Output from COMSOL Multiphysics

Limitations

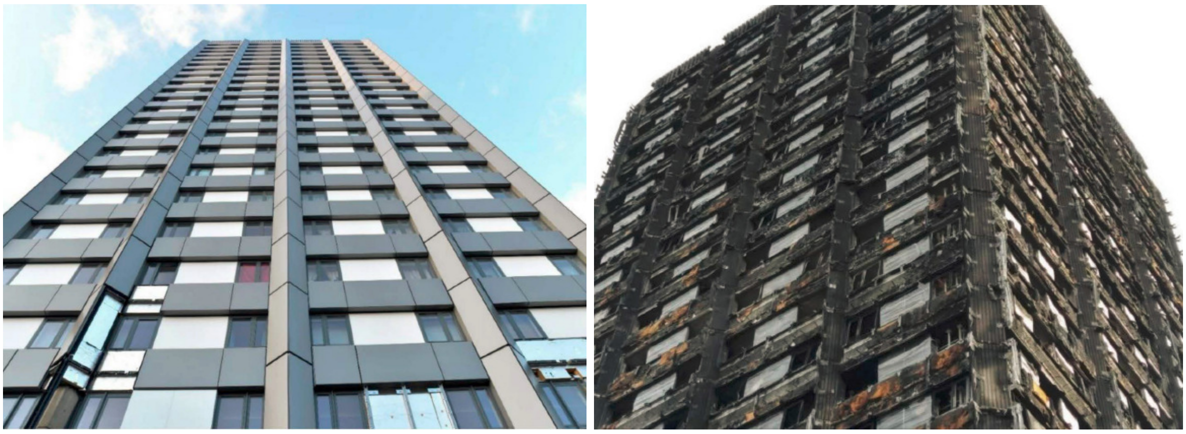
From 9 minutes onwards, it is uncertain how the facade will behave when exposed to the high temperatures induced by the fire. Deformations of the materials, such as the softening- and melting behavior of EPS cannot be modelled. Consequently, it is also an uncertainty whether the cementitious layer and the brick slips remain in their place, once the EPS deforms due to the high temperatures.

As mentioned before, it is not possible to model the flame itself in COMSOL Multiphysics. Hence, for this simulation, the temperature of the external flame is assumed to be constant over the entire section and over time. It should be taken into account that actual external flames are much more dynamic than the input for this simulation allowed, and it is therefore possible that critical temperatures (e.g. the melting temperature of EPS) may be reached sooner or later than this simulation has shown in reality.

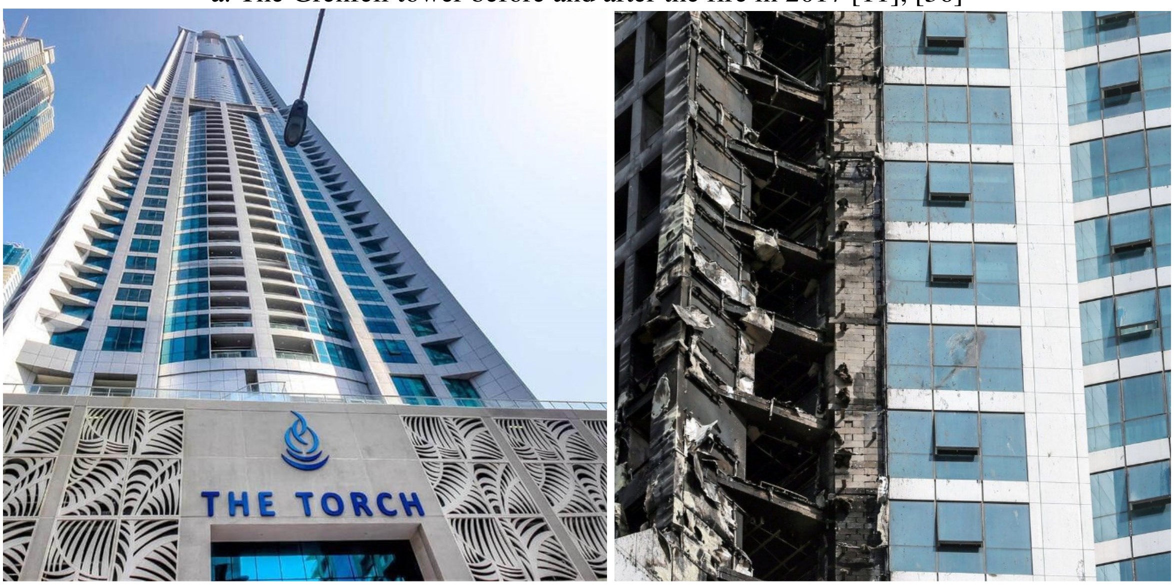
5. Thermal simulation in COMSOL Multiphysics for different cladding types

5.1 Aluminum Composite Material (ACM) cladding

Prior mentioned is how aluminum composite material (ACM) panels with a polyethylene (PE) core, combined with combustible PIR insulation, fueled the facade fire that occurred to the Grenfell tower in 2017. Also for many other events, as listed in Table 1, ACM panels played in important role in the fire spread via facades. The before and the after of the Grenfell fire and the Torch fire have been provided in Figure 23a and Figure 23b, respectively, to show the destruction by the facade fires to the cladding and underlying layers. The severity of the damage is why this cladding type is also modelled in COMSOL Multiphysics, and for the completeness, also if panels were applied with a mineral wool (MW) core instead of a PE core.



a. The Grenfell tower before and after the fire in 2017 [11], [36]



b. The Torch tower before and after the fire in 2017 [26], [65]

Figure 23. ACM-PE cladding before and after a facade fire

Again, in COMSOL Multiphysics, the 2D space dimension is selected under Model Wizard. The Physics used is heat transfer in solids and fluids (ht), as the construction consists of both solid and fluid materials. The chosen study is time dependent in order to be able to simulate changes that occur over time.

After setting up the model space, the actual model is build in the Model Builder. As this is a 2D-model and the desired outcome is data on one dimensional heat transfer, a section of only 1 m of facade is modeled. In Table 7 and 8, the model configurations are summarized for both cladding types (ACM-PE and ACM-MW). The input for the material properties is combined from pre-set properties and properties retrieved from internet [66], [67]. The heat resistance by the cavity (R_{cavity}) is assumed to be 0.17 m²K/W [68], and from this value, the thermal conductivity of the air cavity is calculated. This is done by multiplying the U-value (= 1 / R_{cavity}) with the cavity thickness, resulting in a thermal conductivity of 1.029 W/mK for the specific case.

The geometry is shown in Figure 24, with from top to bottom the ACM panel, the cavity and the EPS layer. As both EPS and PIR, as used in the actual Grenfell facade, are both highly combustible in the event of fire and the thermal effect for the underlying facade layers is not of interest, it is chosen to keep the EPS layer as a constant.

Table 7. Model configurations for COMSOL Multiphysics [66], [67]

		Thickness [m]	Coordinates		Density [kg/m³]	Heat capacity [J/kgK]	Thermal conductivity [W/mK]
			x	y			
EPS layer		0.200	0.000	0.000	11.5	1450	0.05
Cavity		0.175	0.000	0.200	1.29	1000	1.029
ACM panel	Aluminum	0.001	0.000	0.375	2700	900	238
	PE core	0.004	0.000	0.376	930	1900	0.29
	Aluminum	0.001	0.000	0.380	2700	900	238

Table 8. Model configurations for COMSOL Multiphysics [66], [67]

		Thickness [m]	Coordinates		Density [kg/m³]	Heat capacity [J/kgK]	Thermal conductivity [W/mK]
			x	y			
EPS layer		0.200	0.000	0.000	25	1450	0.035
Cavity (air)		0.175	0.000	0.200	1.29	1000	1.029
ACM panel	Aluminum	0.001	0.000	0.375	2800	880	237
	Mineral wool	0.004	0.000	0.376	250	850	0.06
	Aluminum	0.001	0.000	0.380	2800	880	237

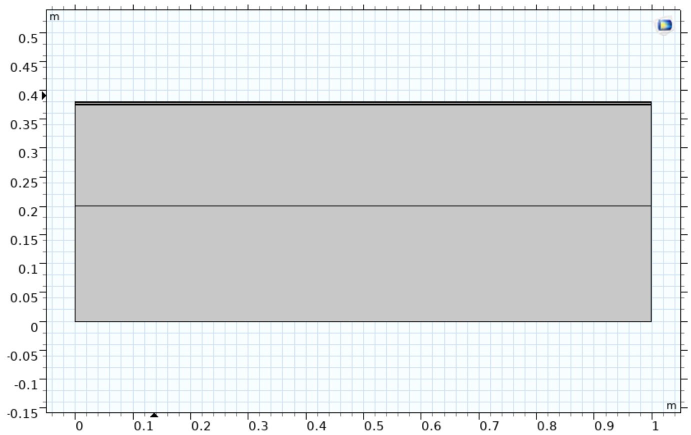


Figure 24. Geometry of the modelled Grenfell facade (ACM-PE)

The initial temperature is 20 °C (= 293.15 K). At t = 0, the temperature at the exterior surface of the ACM panel is changed to 550 °C (= 823.15 K). Again, this indicates the moment where external flaming occurs. The temperature at the cold side of the wall remains 20 °C (= 293.15 K) during the simulation. For the surfaces at both sides of the wall construction, convective heat flux is selected. The heat transfer coefficient applied is the external natural convection for vertical walls, with a length of 1 m. The pressure is kept constant at 1 Pa.

The simulations are run for 1200 seconds, with a time step of 60 seconds.

The results are presented in the plot in Figure 25 for ACM-PE and in the plot in Figure 26 for ACM-MW. Visualized is only the conductive transfer of heat through all layers. From the Figure 25, it is retrieved that the temperature on the surface of the EPS layer has reached the melting temperature of EPS within 8 minutes (> 373.15 K within 480 seconds). For facades with ACM-MW panels applied, this temperature is reached earlier, due to the higher conductivity in ACM panels with an MW-core compared to the conductivity in ACM panels with a PE-core. According to the results as presented in Figure 23, the temperature on surface of the EPS layer reaches the melting temperature of EPS within 7 minutes (420 seconds). For both facade types, the ignition temperature for EPS (633.15 K) is not reached within 20 minutes.

It should be taken into account that conductive heat transfer is not the sole mode of heat transfer. As also convection and radiation play a role in the heat transfer, especially now that a cavity is involved, the outcome from COMSOL Multiphysics is not representative anymore. It could be expected that the heat transfer through the materials and air layer increases when considering all methods of heat transfer.

The second uncertainty is the behavior of the material under the high temperature exposure, as this cannot be modelled in COMSOL Multiphysics. First of, potential failure of the ACM panels. Previous incidents showed melting of the aluminum layer and combustion of the PE core of the ACM panels, which of course changes the outcome of a facade fire significantly. It remains uncertain how ACM panels with a non-combustible MW core would behave under the high temperatures coming from external flames, especially for external flames with higher RHR-values than the 30 kW the material was tested for.

Secondly, the ignition temperature of the EPS insulation layer may not be reached within 20 minutes, so this will likely not cause ignition of the insulation layer. The melting of the EPS layer is also not necessarily a threat for the facade construction, as the ACM panels are fastened to the concrete facade and not to the EPS insulation layer. However, if flames can reach the (melting) EPS layer, thus directly or because of melting of the material, they will definitely ignite the EPS layer, causing a cavity fire.

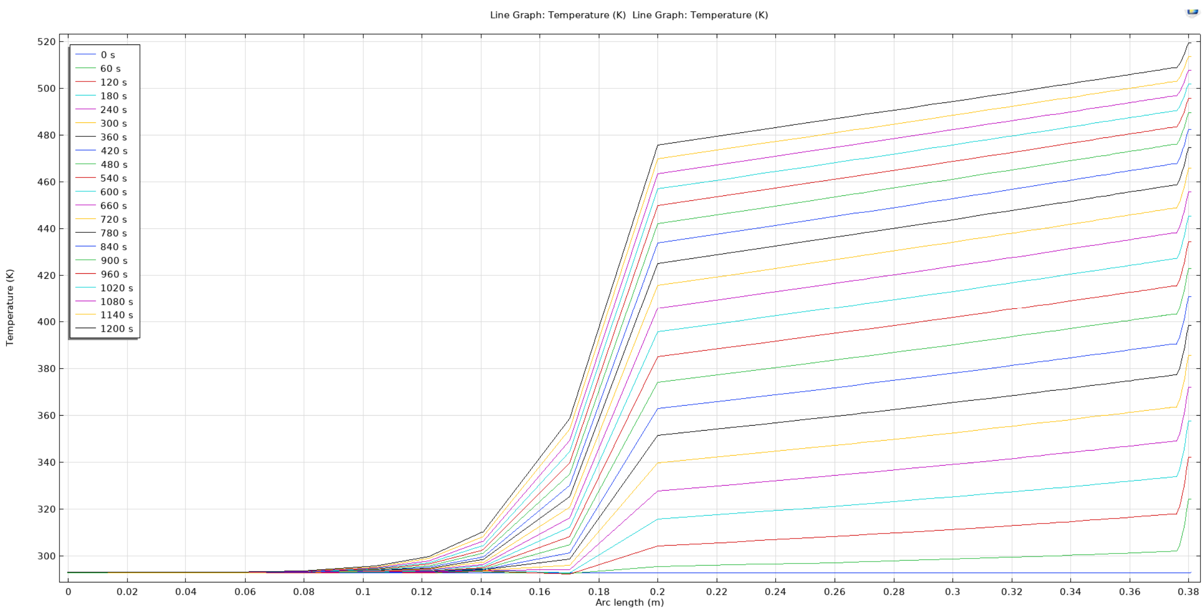


Figure 25. Output from COMSOL Multiphysics for ACM-PE

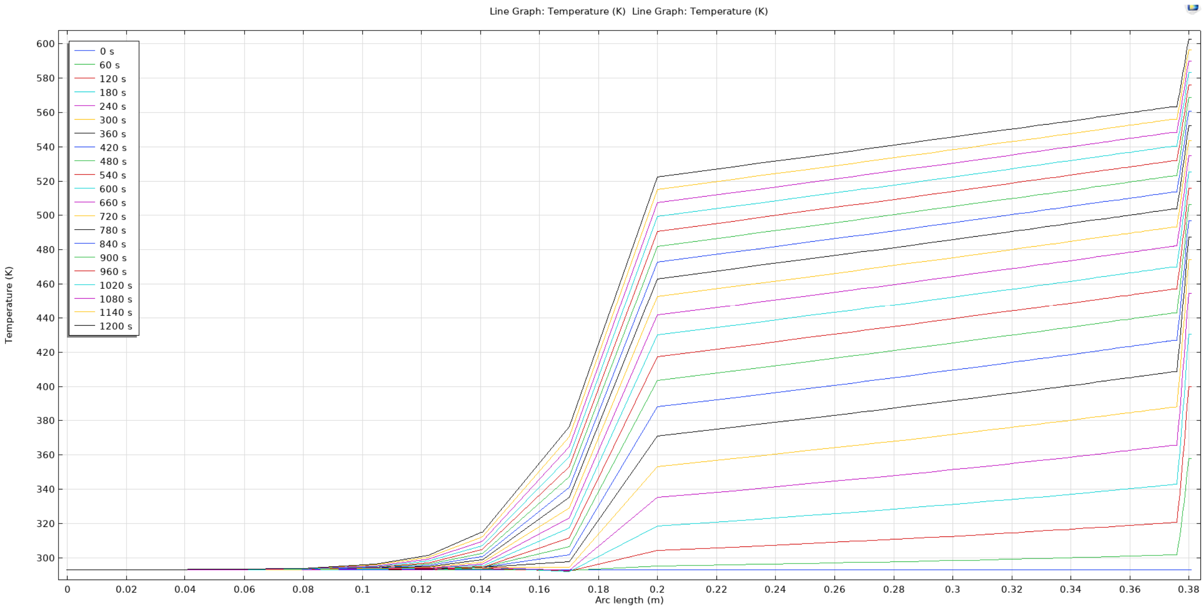


Figure 26. Output from COMSOL Multiphysics for ACM-MW

5.2 High Pressure Laminate (HPL) cladding

One less infamous facade fire that took place in the United Kingdom, was the facade fire that blazed around the student complex Cube in Bolton in 2019. This facade was not cladded with ACM panels, but with equally flammable High Pressure Laminate (HPL) cladding. This material consists of layering sheets of wood or paper fiber with a resin, bonded under heat and pressure. Similarly to ACM panels, HPL panels are available in a wide range of colors and finishes. These panels are typically installed with a ventilated cavity behind the panels [69], [70].

Regarding the fire class of this plastic composite, it typically depends on the thickness of the material. Untreated, HPL panels are either fire class C or D, implying that the facade cladding will fuel a facade fire [71]. The aftermath of the Cube fire is seen in Figure 27. With the addition of chemicals, the panels have an increased fire resistance and will achieve conformation to fire class B, potentially preventing fires such as the Cube fire.


Figure 27. The HPL cladding of the Cube before [72] and after the fire in 2019 [73]

Again, in COMSOL Multiphysics, the 2D space dimension is selected under Model Wizard. The Physics used is heat transfer in solids and fluids (ht), as the construction consists of both solid and fluid materials. The chosen study is time dependent in order to be able to simulate changes that occur over time.

After setting up the model space, the actual model is build in the Model Builder. As this is a 2D-model and the desired outcome is data on one dimensional heat transfer, a section of only 1 m of facade is modeled. In Table 9, the model configurations are summarized. The input for the material properties is combined from pre-set properties and properties retrieved from internet [66], [67], [74]. The heat resistance by the cavity (R_{cavity}) is assumed to be 0.17 m²K/W [68], and from this value, the thermal conductivity of the air cavity is calculated. This is done by multiplying the U-value (= 1 / R_{cavity}) with the cavity thickness, resulting in a thermal conductivity of 0.147 W/mK for the specific case. The geometry for this simulation is shown in Figure 28, with from top to bottom the HPL panel, the cavity and the EPS layer.

Table 9. Model configurations for COMSOL Multiphysics [66], [67], [74]

	Thickness [m]	Coordinates		Density [kg/m³]	Heat capacity [J/kgK]	Thermal conductivity [W/mK]
		x	y			
EPS layer	0.200	0.000	0.000	11.5	1450	0.05
Cavity (air)	0.025	0.000	0.200	1.29	1000	0.147
HPL cladding panel	0.008	0.000	0.225	1350	1500	0.3

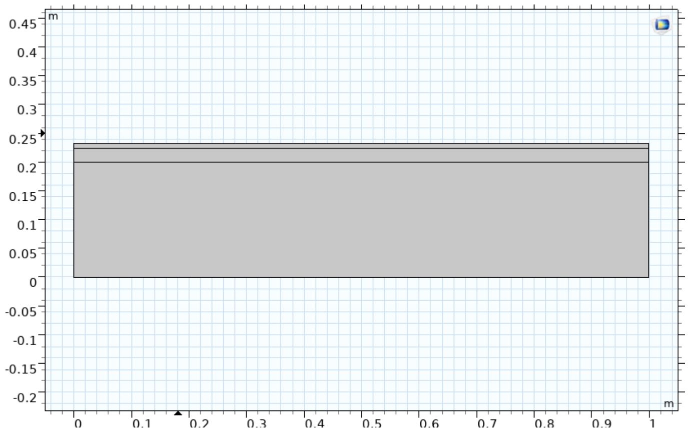


Figure 28. Geometry of the modelled “The Cube”-facade (HPL)

The initial temperature is 20 °C (= 293.15 K). At t = 0, the temperature at the exterior surface of the ACM-panel is changed to 550 °C (= 823.15 K). Again, this indicates the moment where external flaming occurs. The temperature at the cold side of the wall remains 20 °C (= 293.15 K) during the simulation. For the surfaces at both sides of the wall construction, convective heat flux is selected. The heat transfer coefficient applied is the external natural convection for vertical walls, with a length of 1 m. The pressure is kept constant at 1 Pa.

The simulations are run for 1200 seconds, with a time step of 60 seconds.

The outcome from COMSOL Multiphysics is shown in Figure 29. Only the conductive heat transfer is visualized in this plot. From the graph, it is retrieved that the temperature on the surface of the EPS insulation layer reaches the melting temperature of EPS within 11 minutes (> 373.15 K within 660 seconds).

However, as the HPL cladding is rated as fire class C or D, it should never be used in combination with an EPS insulation layer. Fire tests have shown how the material contributes to a facade fire, acting as fuel [75]. Yet, the material was approved in official fire safety tests, admittedly with non-combustible insulation (e.g. mineral wool) [76].

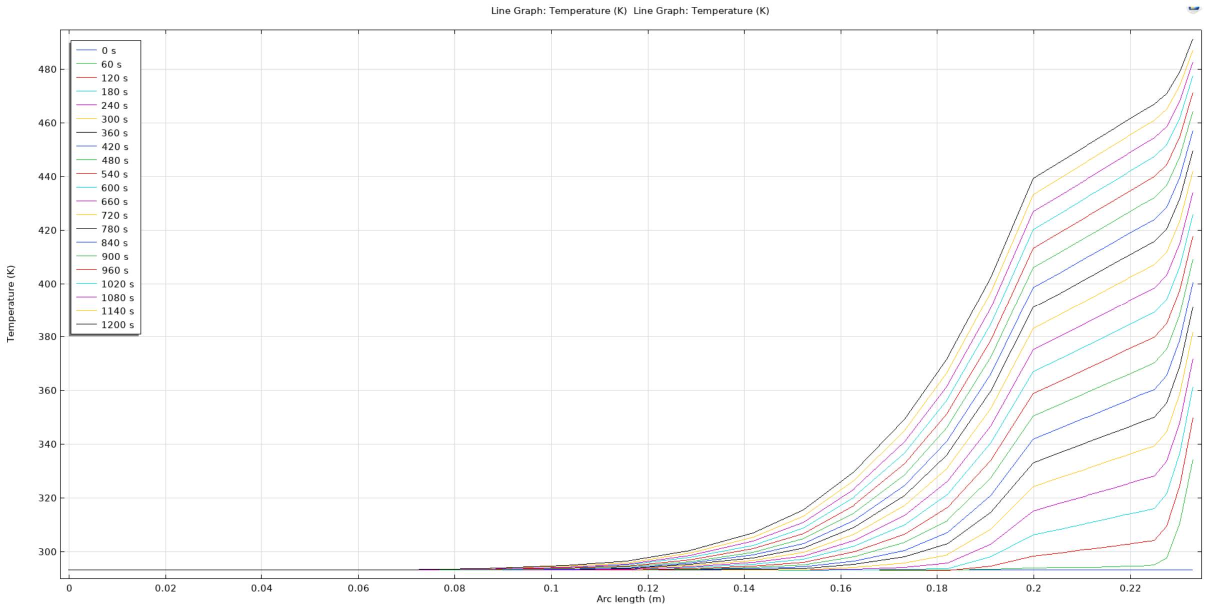


Figure 29. Output from COMSOL Multiphysics

Limitations

The (thermal simulation) results from COMSOL Multiphysics for both the ACM panels and the HPL panels showed reliable results regarding the conduction through the facade construction. However, as previously mentioned, the result is not realistic as the effects of convection and radiation are neglected. This is especially of interest when the facade construction includes a cavity. In addition, it is not possible to take into account material- and construction behavior under high temperature exposure in COMSOL Multiphysics. The simulation gives therefore an optimistic result compared to reality.

It would be interesting to further analyze the spread of heat along the facade and in the cavity via a computational fluid dynamics (CFD) analysis, e.g. by using Fire Dynamics Simulator (FDS) [44], [77]–[82]. By using FDS, it becomes possible to gain more insight on how a cavity fire will develop itself, regarding the flame height and radiative- and convective heat fluxes throughout the cavity, taken over the rate of heat release or time, respectively [78], [81], [82]. Also, the dynamic temperature of the cavity fire can be retrieved from FDS, at different heights. This would help making a better prediction on the behavior of the facade materials in the event of fire, as the temperature that these materials are exposed to, is now predicted with FDS [77], [80].

6. Design recommendations

For the "De Ananas"-complex in Leiden, recommendations can be done on the Strikolith-facade system. Shown is how this facade construction consists of brick slips, backed by a cementitious layer. The thinness of this cladding material puts the fire resilience of the facade system up to debate. The same goes for the backing system: a high-level risk is introduced when they are supported by glass-reinforced plastic or directly by the insulation layer. Medium-level risk is induced if the brick slips are backed on magnesium oxide panels or cement particle board, the latter used for the facade construction of the "De Ananas" complex. Brick slips supported by a steel backing offer the lowest risk, due to the high melting temperature of steel [83].

It is likely that the currently designed Strikolith system would fall out when an external flame would threaten the facade, due to lack of support by the weakened cementitious backing of the brick slip layer (due to the high temperature exposure [59]), or due to lack of support by the underlying EPS insulation layer, which will melt when the temperature exceeds 100 °C. Either way, the (remainder of the) EPS insulation layer would be directly exposed to the flame, making combustion of this layer inevitable. As the robustness of the Strikolith system cannot be guaranteed in the event of fire, it would have been wiser to opt for a non-combustible insulation material.

If the brick slips were applied to a steel backing, the performance of the facade system regarding fire resistance and high temperature resistance would be increased, as the facade is more likely to stay in place. Mechanical assembly is recommended over adhesive assembly [60]. If the risk of failure of the brick slip construction is minimized, the use of combustible insulation material can be considered. Of course, careful detailing (and in practice, careful building) is necessary to prevent the fire from reaching the combustible EPS layer through seams. To limit the risk of vertical and horizontal fire propagation to all floors and apartments through the flammable EPS insulation layer, it would be wise to still apply mineral wool strips between floors and different apartments (thus fire barriers).

For ACM- and HPL-cladding panels, the design recommendations are slightly different. Firstly, a ventilated cavity is essential in the design of the facade with these cladding types, to avoid moisture problems. To restrict the flame height in cavities in the event of fire, cavity barriers and/or fire stops are highly recommended for facades with a (ventilated) cavity. Please note that fire stops are only useful when the outer facade layer will not fall out in the event of fire. If the outer facade layer were to fall out, the fire stops would lose their function and would only give a false sense of fire safety.

However, cavity barriers should be applied around facade openings, to prevent the fire from penetrating into the cavity at an initial stage. This cavity barrier should stay in tact for at least the same amount of time as the panels would.

A second threat that comes with the application of ACM- and HPL- panels is the poor fire resistance of the panels. If the panels have not had any interventions regarding their fire safety, the fire class of ACM- and HPL panels is D/E [36], [84] and C/D [71], respectively. The fire class of ACM panels can be improved to fire class B and A2 with a mineral-filled core and non-combustible polymer adhesives [84]. With the addition of fire retardant chemicals, a fire class B can be achieved [71]. However, these panels would still offer a medium-level risk [83] and are likely to fall out in the event of fire, it is recommended to only design facades with ACM- and HPL-panels in combination with non-combustible insulation material.

No matter what facade construction is used in a design, one last important aspect regarding the detailing should be highlighted. It has been shown in this project that there is a significant probability that a compartment fire will result in an external flame. Therefore, the focus has been on the effect of this external flame on the facade materials in thermally thin facade constructions, whether these materials are combustible or non-combustible. This with the aim to better understand and hopefully prevent fire spread via thermally thin facades. As combustion of facade materials cannot always be excluded, it should be taken into account that the toxic smoke and gases may enter other compartments, potentially leading to unconsciousness and ultimately even death of occupants of these other compartments [85]. It is therefore of importance that attention is paid regarding proper (airtight) sealing of the facade. This to ensure personal safety of all occupants in a building.

7. Conclusions

Repeatedly, fire spread via facades and cavities has been an issue for (high rise) residential buildings. The term for this spread of fire around the interior fire compartmentation via facades and cavities is flanking. The research objective of this report has been to gain insight on how thermally thin cladding systems affect the risk of flanking fires. Based on the findings, design recommendations for fire safe facade design have been made, in order to prevent the occurrence of flanking fires and this way, reduce the risk on fire spread to other fire compartments.

A case study has been performed on "De Ananas", to get an estimate on the probability of the occurrence of an external flame and the potential threat that this external flame would form on the facade. From the simulation of the base scenario in OZone, it could be concluded that no external flame would occur. However, a sensitivity analysis showed that for different scenarios, the outcome would be different (thus that an external flame would occur). The probability approach based on this sensitivity analysis showed that the probability of an external flame occurring is 52.9%. There is a 46.5% probability that an external flame occurs with an RHR higher than the 30 kW/m that the facade materials have been tested for.

Because of the significant probability that an external flame would occur in the event of fire, the facade of "De Ananas" has been simulated in COMSOL Multiphysics in order to observe transmission of heat through the facade (considering an external flame of 550 °C). The simulation showed that within 9 minutes, the melting temperature of the underlying EPS layer can be reached. From this simulation, along with the results from the OZone simulations, it is concluded that the behavior of the facade construction when exposed to an external flame may differ from the behavior it showed during the fire tests, prevention of failure in the event of fire cannot be guaranteed.

The same simulation model in COMSOL Multiphysics has been used for two other types of thermally thin facades, namely ACM panels and HPL panels. However, the simulation results are not satisfactory for these facade types, as the simulation model offered too little possibility to accurately model the other modes of heat transfer (i.e. convection and radiation). Convection and radiation should not be neglected for facade constructions with a cavity, as they play a prominent role regarding the heat transfer inside the cavity. Therefore, it can be said that using this COMSOL Multiphysics model only holds for constructions where conduction is the main way of heat transport. For facade constructions with a cavity, it is recommended to model these constructions in more advanced simulation models, e.g. in FDS.

It could be interesting to reconsider the testing for the fire classification of materials and facade systems, especially for exposure to a higher rate of heat release. Testing for exposure to higher rate of heat release could cover some important uncertainties regarding the behavior of materials and facade systems, such as deformation and melting. Not a lot can be said about the behavior of materials or facade systems when they are exposed to an actual fire when they have been exposed to a fire with a rate of heat release 30 kW. Therefore, no strong assumptions can be made on the risk of flanking (both for the case study and in general).

In addition, it can be concluded that even if a building conforms to the Dutch Building Code, different approaches should be used to get a clearer indication of the risk induced by a fire, especially with respect to flanking. This research shows that the probability of an external flame occurring can be larger than initially expected, and in what time this external flame would threaten the facade considering the material properties of the facade materials.

As mentioned, design recommendations have been made for the design of thermally thin facades, limiting the risk on flanking for facades with an outer layer of ACM cladding, HPL cladding or brick slip cladding. These recommendations combine both materialization and building technology. In general, it is recommended to use combustible cladding solely with a non-combustible insulation material and to always make sure that fire penetration into a cavity is prevented with a cavity barrier. Fire stops and cavity barriers between floors and compartments should be used to prevent further fire spread via the cavity, but are effective only when the outer facade layer stays in tact. If the latter cannot be guaranteed, the fire stops and/or cavity barriers may provide a false sense of safety. For the "De Ananas"-complex specifically, it is proposed that the brick slips are backed by a metal construction rather than the cementitious layer, as this increases the fire resistance of the facade construction. The alternative is to apply non-combustible insulation material (e.g. mineral wool) rather than EPS for the insulation layer, also with the aim to increase the fire resistance of the facade.

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Appendix A: BZK risk tool

Globale risico-schatting voor brandbare gevels

dGm[R]

Globale risico-schatting voor brandbare gevels	Factor	Gebouw 1	Gebouw 2	Gebouw 3	Gebouw 4	Gebouw 5
Gevelkenmerken						
1a. Brandvoortplanting buitenblad		1	1	1	1	1
Toplaag <3 vol.% brandbaar	1					
Toplaag 3-30 vol.% of kopse zijde >30 vol.% brandbaar	4					
Toplaag >30 vol.% brandbaar	16					
Onbekend	16	Toelichting	Toelichting	Toelichting	Toelichting	Toelichting
1b. Brandvoortplanting buitenblad *1		1	1	1	1	1
Geen risico-reducerende factor	1					
Effectieve gevelonderbreking op elke verdieping *2	0,25	Toelichting	Toelichting	Toelichting	Toelichting	Toelichting
2a. Brandvoortplanting geventileerde gevelspouw		1	1	1	1	1
Geen geventileerde spouw	1					
Toplagen samen <3 vol.% brandbaar	1					
Toplagen samen 3-30 vol.% brandbaar	2					
Toplagen samen >30 vol.% brandbaar	4					
Onbekend	4	Toelichting	Toelichting	Toelichting	Toelichting	Toelichting
2b. Brandvoortplanting geventileerde gevelspouw *1		1	1	1	1	1
Geen risico-reducerende factor	1					
Effectieve spouwonderbrekingen op elke verdieping *3	0,5	Toelichting	Toelichting	Toelichting	Toelichting	Toelichting
Gebouw(gebruik)-kenmerken						
3. Gebruiksfunctie		1	1	1	1	1
Gezondheidszorg-bedgebied, wonen voor zorg of celfunctie	8					
Kinderopvang met bedgebied	4					
Woonfunctie in woongebouwen, logiesfunctie in logiesgebouwen	4					
Overige gebruiksfuncties	1	Toelichting	Toelichting	Toelichting	Toelichting	Toelichting
4. Hoogte gebouw		1	1	1	1	1
Gebouwhoogte <15m	1					
Gebouwhoogte 15m-40m	2					
Gebouwhoogte 40m-100m	4					
Gebouwhoogte >100m	6	Toelichting	Toelichting	Toelichting	Toelichting	Toelichting
5a. Ligging vluchtroutes		1	1	1	1	1
Twee trappehuizen op afstand >H/2	1					
Twee trappehuizen op afstand <H/2 in twee kernen	2					
Twee trappehuizen op afstand <H/2 in één kern	4					
Eén trappenhuis	8	Toelichting	Toelichting	Toelichting	Toelichting	Toelichting
5b. Ligging vluchtroutes *1		1	1	1	1	1
Geen risico-reducerende factor	1					
Eén trappenhuis zonder gevelopeningen	0,5					
Twee trappenhuizen zonder gevelopeningen	0,25	Toelichting	Toelichting	Toelichting	Toelichting	Toelichting
6. Extra voorzieningen		1	1	1	1	1
Standaard Bouwbesluit / geen extra voorzieningen	1					
BMI met volledige bewaking waar dit niet vereist is	0,25					
Blusinstallatie	0,25					
Brandwerende gevel	0,25	Toelichting	Toelichting	Toelichting	Toelichting	Toelichting
		1	1	1	1	1

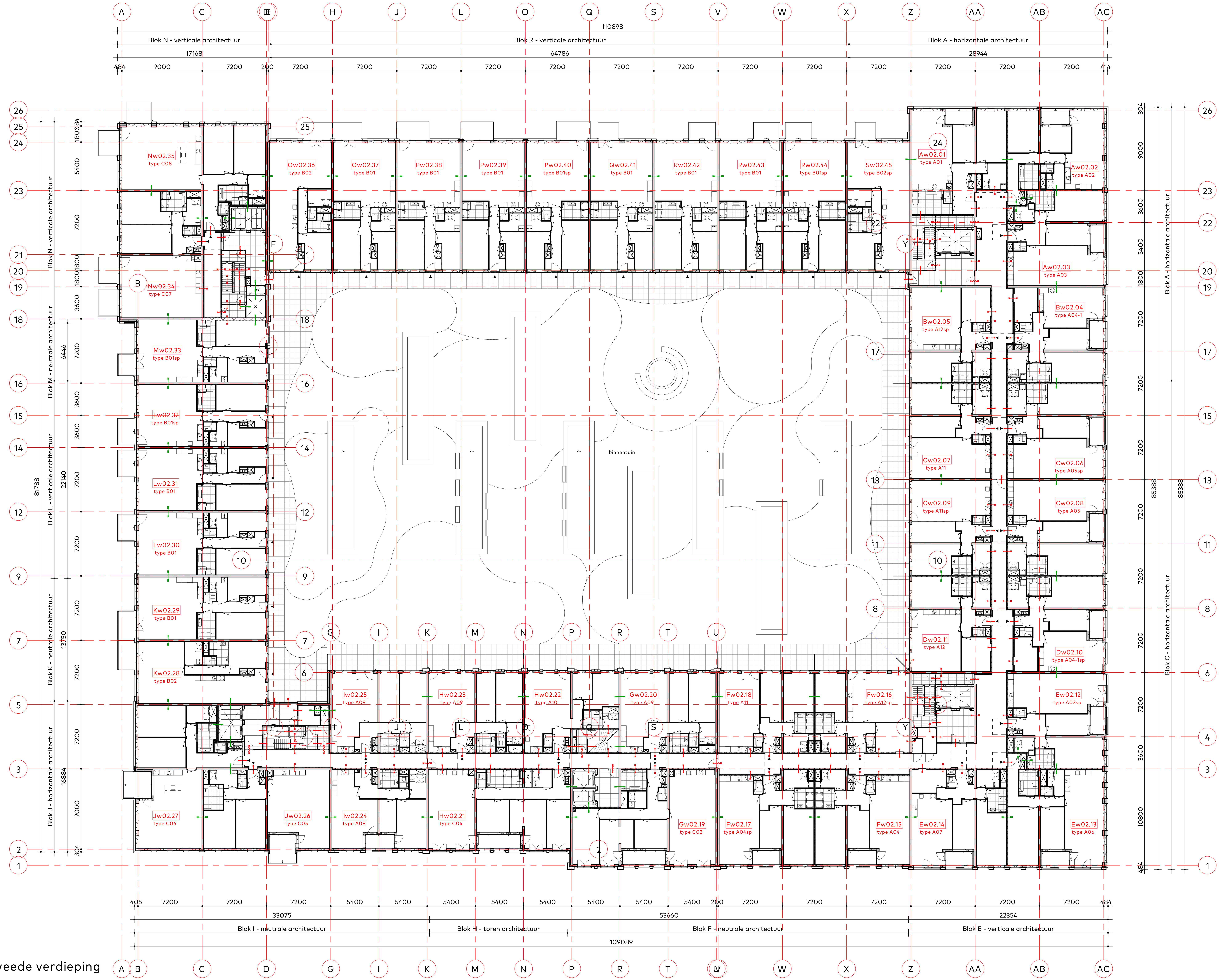
Risico-categorieën				
Weging	< 50	50 - 200	200 - 800	> 800
Code	Groen	Geel	Oranje	Rood

*1: Een factor 1 staat voor een zeer laag risico en kan daarom niet verder worden verlaagd met een risico-reducerende maatregel, dus wordt de eindscore berekend met: 1a x 1b ≥ 1, 2a x 2b ≥ 1 en 5a x 5b ≥ 1

*2: Effectieve gevelonderbrekingen: balkon/uitkraging op elke verdieping, breed >0,5m en 'brandvast', of horizontale raamstrook, hoog >1m, op elke verdieping. Brandvast: <3 vol.% brandbaar en niet-smeltend.

*3: Effectieve spouwonderbrekingen: spouwonderbreking op elke verdieping, met buitenblad en ophanging daarvan 'brandvast' (<3 vol.% brandbaar en niet-smeltend).

Appendix B: Floor plan (Third floor, 1:200)



tweede verdieping

typologien totaal

typologie	aantal
A01	7
A02	7
A03	7
A03sp	6
A04	10
A04-1	1
A04-1sp	1
A04sp	10
A05	5
A05sp	5
A06	10
A07	7
A08	6
A09	18
A10	6
A11	12
A11sp	6
A12	6
A12sp	12
A13	1
A13sp	1
A14	1

typologien totaal

typologie	aantal
A14sp	1
A15	4
A16	2
A17	1
B01	54
B01sp	24
B02	12
B02sp	6
B03	4
C01	1
C02	1
C03	5
C04	13
C05	8
C06	8
C07	12
C08	12
C09	10
C10	7
C11	9
C12	2
C13	2

typologien totaal

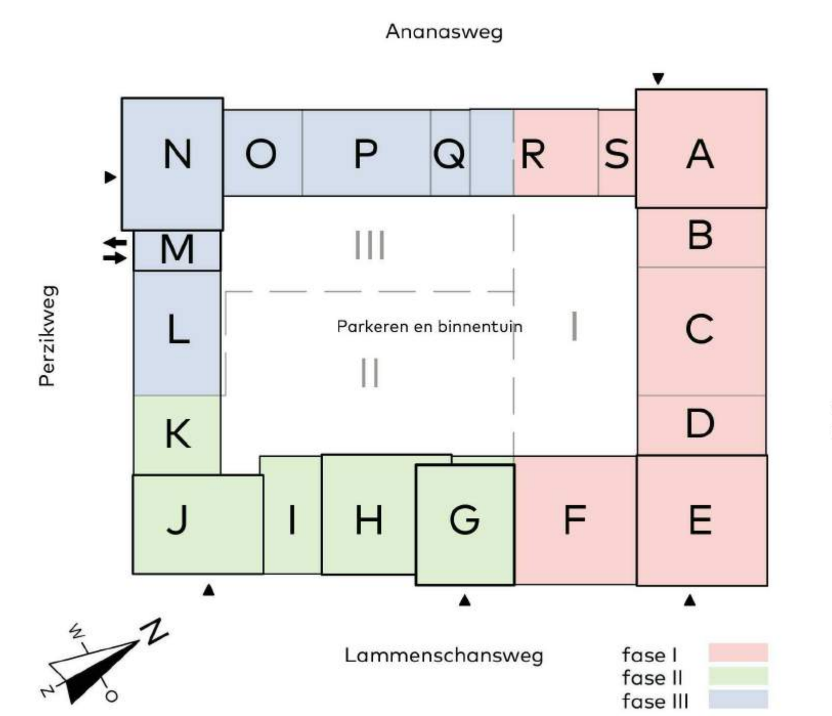
typologie	aantal
M01	7
M01sp	3
M02	1
M03	1
P01	2
R01	1
R02	1
R03	1
R04	1
S01	1
S02	1
S03	1
S04	1
S05	1
S06	1
S07	1
S08	1
S09	1
S10	1
S11	1
S12	1
totaal: 373	

typologien 02_tweede verdieping

typologie	aantal
A01	1
A02	1
A03	1
A03sp	1
A04	1
A04-1	1
A04-1sp	1
A04sp	1
A05	1
A05sp	1
A06	1
A07	1
A08	1
A09	3
A10	1

typologien 02_tweede verdieping

typologie	aantal
A11	2
A11sp	1
A12	1
A12sp	2
B01	9
B01sp	4
B02	2
B02sp	1
C03	1
C04	1
C05	1
C06	1
C07	1
C08	1
totaal: 45	



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architecten

Definitief Ontwerp

project:
appartementen De Ananas

locatie & opdrachtgever:
Ananasweg te Leiden
voor De Raad Vastgoed

onderwerp:
overzichtstekening 2e verdieping

schaal: 1:200
datum: 15/05/2019
formaat: 60x100
getekend: mve

wijziging: D. 06/07/2020
werknummer: 15808
tekeningnummer: 2_02_01

adres:
van Egmond Architecten B.V.
Gooweg 5
2201 AX Noordwijk

contact:
+31 (0)71 36 19 700
info@vanegmondarchitecten.nl
www.vanegmondarchitecten.nl

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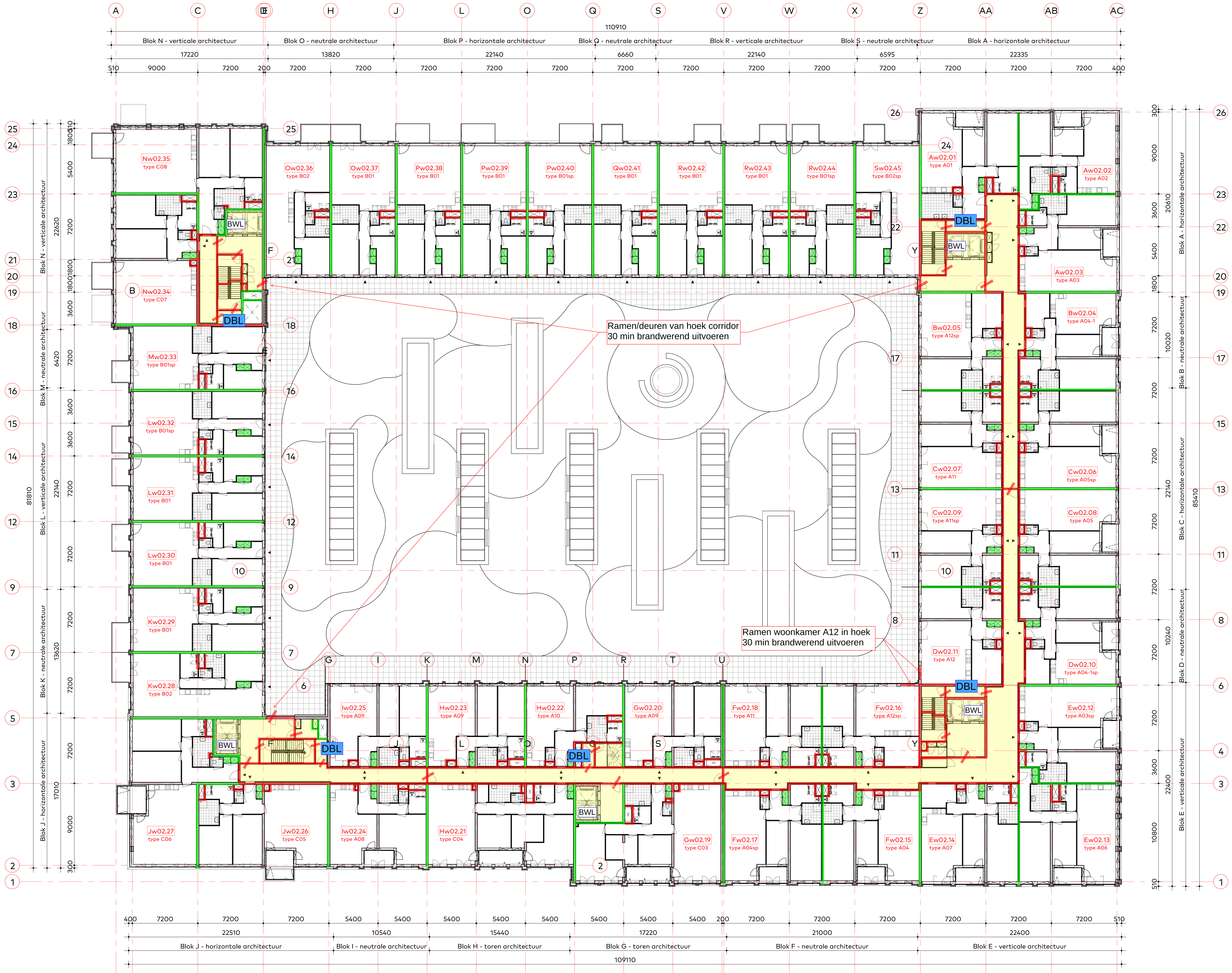
Appendix C: Floor plan, fire compartmentation indicated (Third floor, 1:200)



tweede verdieping

typologien totaal	
typologie	aantal
A01	7
A02	7
A03	7
A03sp	6
A04	6
A04-1	5
A04-1sp	5
A04sp	6
A05	5
A05sp	5
A06	10
A07	7
A08	6
A09	18
A10	6
A11	12
A11sp	6
A12	6
A12sp	12
A13	1
A13sp	1
A14	1

typologien totaal	
typologie	aantal
A14sp	1
A15	4
A16	3
B01	54
B01sp	24
B02	12
B02sp	6
B03	4
C01	1
C02	1
C03	5
C04	13
C05	8
C06	8
C07	12
C08	12
C09	10
C10	7
C11	9
C12	2
C13	2
M01	7

typologien totaal	
typologie	aantal
M01sp	3
M02	1
M03	1
P01	2
R01	1
R02	1
R03	1
R04	1
S01	1
S02	1
S03	1
S04	1
S05	1
S06	1
S07	1
S08	1
S09	1
S10	1
S11	1
S12	1
S13	1
totaal: 374	

typologien 02_tweede verdieping	
typologie	aantal
A01	1
A02	1
A03	1
A03sp	1
A04	1
A04-1	1
A04-1sp	1
A04sp	1
A05	1
A05sp	1
A06	1
A07	1
A08	1
A09	3
A10	1

typologien 02_tweede verdieping	
typologie	aantal
A11	2
A11sp	1
A12	1
A12sp	2
B01	9
B01sp	4
B02	2
B02sp	1
C03	1
C04	1
C05	1
C06	1
C07	1
C08	1
totaal: 45	

CAUBERG HUYGEN

Principe brandveiligheid

Ananasweg Lammenschans
20151553

Legenda

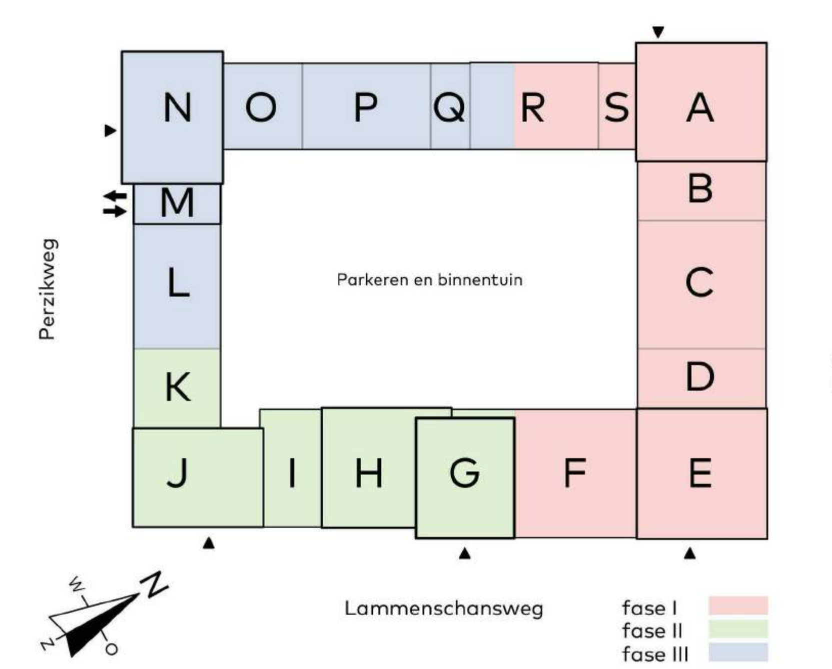
- 60 min WBDBO
- 60 min WBDBO en zelfsluitende deuren
- 30 min WBDBO
- 30 min WBDBO en zelfsluitende deuren
- Vluchtroute
- Aanvalsroute brandweer
- Vluchtroute

Alle doorvoeringen door brandscheidingen dienen eveneens brandwerend uitgevoerd te worden (d.m.v. voorzieningen als brandkleppen en manchette etc.) De brandwerendheid dient gelijk te zijn aan de brandwerendheid van de vloer/wand waar de doorvoering doorheen gaat.

Ter plaatse van meterkasten dient een WBDBO van 60 minuten tussen de verdiepingen aanwezig te zijn. Er dient een brandscheiding ter plaatse van de woningscheidende vloer gerealiseerd te worden met WBDBO van 60 min.

Ook ter plaatse van technische schachten dient een WBDBO van 60 minuten tussen de verdiepingen aanwezig te zijn. Dit kan gerealiseerd worden door een brandscheiding met WBDBO 30 minuten (tweezijdig getoetst, van woning naar schacht en van schacht naar woning) conform NEN 6068.

DBL Droge blusleiding
BWL Brandweerlift



van Egmond,
architecten

Definitief Ontwerp

project:	locatie & opdrachtgever:	onderwerp:
appartementen De Ananas	Ananasweg te Leiden voor De Raad Vastgoed	overzichtstekening 2e verdieping

schaal:	datum:	formaat:	getekend:
1:200	18/01/2019	60x100	mve

wijziging:	werknummer:	tekeningnummer:
	15808	2_02_01

adres:
van Egmond Architecten B.V.
Gooweg 5
2201 AX Noordwijk

contact:
+31 (0)71 36 19 700
info@vanegmondarchitecten.nl
www.vanegmondarchitecten.nl

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Appendix D: BZK risk tool for De Ananas

Globale risico-schatting voor brandbare gevels

Globale risico-schatting voor brandbare gevels	Factor	Segment A (hoek)	Segment F	Segment G (toren)	Segment H (toren)	Segment N (hoek)	Segment S
Gevelkenmerken							
1a. Brandvoortplanting buitenblad		**16**	**16**	**16**	**16**	**16**	**16**
Toplaag <3 vol.% brandbaar	1						
Toplaag 3-30 vol.% of kopse zijde >30 vol.% brandbaar	4						
Toplaag >30 vol.% brandbaar	16						
Onbekend	16	strikolith met dikte van 10 mm op brandbaar EPS, dus > 30 vol.%	strikolith met dikte van 10 mm op brandbaar EPS, dus > 30 vol.%	strikolith met dikte van 10 mm op brandbaar EPS, dus > 30 vol.%	strikolith met dikte van 10 mm op brandbaar EPS, dus > 30 vol.%	strikolith met dikte van 10 mm op brandbaar EPS, dus > 30 vol.%	strikolith met dikte van 10 mm op brandbaar EPS, dus > 30 vol.%
1b. Brandvoortplanting buitenblad *1		**1**	**1**	**1**	**1**	**1**	**1**
Geen risico-reducerende factor	1						
Effectieve gevelonderbreking op elke verdieping *2	0,25						
2a. Brandvoortplanting geventileerde gevelspouw		**1**	**1**	**1**	**1**	**1**	**1**
Geen geventileerde spouw	1						
Toplagen samen <3 vol.% brandbaar	1						
Toplagen samen 3-30 vol.% brandbaar	2						
Toplagen samen >30 vol.% brandbaar	4						
Onbekend	4	geen spouw	geen spouw	geen spouw	geen spouw	geen spouw	geen spouw
2b. Brandvoortplanting geventileerde gevelspouw *1		**1**	**1**	**1**	**1**	**1**	**1**
Geen risico-reducerende factor	1						
Effectieve spouwonderbrekingen op elke verdieping *3	0,5	n.v.t.	n.v.t.	n.v.t.	n.v.t.	n.v.t.	n.v.t.
Gebouw(gebruik)-kenmerken							
3. Gebruiksfunctie		**4**	**4**	**4**	**4**	**4**	**4**
Gezondheidszorg-bedgebied, wonen voor zorg of celfunctie	8						
Kinderopvang met bedgebied	4						
Woonfunctie in woongebouwen, logiesfunctie in logiesgebouwen	4						
Overige gebruiksfuncties	1	woonfunctie	woonfunctie	woonfunctie	woonfunctie	woonfunctie	woonfunctie
4. Hoogte gebouw		**2**	**2**	**4**	**4**	**2**	**2**
Gebouwhoogte <15m	1						
Gebouwhoogte 15m-40m	2						
Gebouwhoogte 40m-100m	4						
Gebouwhoogte >100m	6	24,86m	21,88m	54,66m	48,70m	39,76m	21,88m
5a. Ligging vluchtroutes		**1**	**1**	**8**	**8**	**1**	**2**
Twee trappehuizen op afstand >H/2	1						
Twee trappehuizen op afstand <H/2 in twee kernen	2						
Twee trappehuizen op afstand <H/2 in één kern	4						
Eén trappenhuis	8	twee kernen in segment A	twee kernen in segment E en wokkeltrap in segment G	wokkeltrap in segment G	wokkeltrap in segment G	twee kernen in segment N	kern in segment A en kern in segment N (afstand ong. 72m via gallerij)
5b. Ligging vluchtroutes *1		**0,25**	**0,25**	**0,5**	**0,5**	**0,25**	**0,25**
Geen risico-reducerende factor	1						
Eén trappenhuis zonder gevelopeningen	0,5						
Twee trappenhuizen zonder gevelopeningen	0,25	twee trappenhuizen zonder gevelopeningen	twee trappenhuizen zonder gevelopeningen	wokkeltrap, dus één trappenhuis	wokkeltrap, dus één trappenhuis	twee trappenhuizen zonder gevelopeningen	twee trappenhuizen zonder gevelopeningen
6. Extra voorzieningen		**1**	**1**	**1**	**1**	**1**	**1**
Standaard Bouwbesluit / geen extra voorzieningen	1						
BMI met volledige bewaking waar dit niet vereist is	0,25						
Blusinstallatie	0,25						
Brandwerende gevel	0,25	alleen droge blusleiding in segment A, geen sprinklers	geen eigen droge blusleiding, ook geen sprinklers	alleen droge blusleiding tussen segment G en H, geen sprinklers	alleen droge blusleiding tussen segment G en H, geen sprinklers	alleen droge blusleiding in segment N, geen sprinklers	geen eigen droge blusleiding, ook geen sprinklers
		128	**128**	**1024**	**1024**	**128**	**128**

Risico-categorieën

Weging	< 50	50 - 200	200 - 800	> 800
Code	Groen	Geel	Oranje	Rood

*1: Een factor 1 staat voor een zeer laag risico en kan daarom niet verder worden verlaagd met een risico-reducerende maatregel, dus wordt de eindscore berekend met: 1a x 1b ≥ 1, 2a x 2b ≥ 1 en 5a x 5b ≥ 1

*2: Effectieve gevelonderbrekingen: balkon/uitkraging op elke verdieping, breed >0,5m en 'brandvast', of horizontale raamstrook, hoog >1m, op elke verdieping. Brandvast: <3 vol.% brandbaar en niet-smeltend.

*3: Effectieve spouwonderbrekingen: spouwonderbreking op elke verdieping, met buitenblad en ophanging daarvan 'brandvast' (<3 vol.% brandbaar en niet-smeltend).

Appendix E: OZone simulation of De Ananas | Base Scenario

OZone V 3.0.4 Report

ANALYSIS

Analysis Name:

File Name:C:\Users\s150415\Documents\1. Subjects\Q2. Masterproject II - fire safety\Case Ananas.ozn

Created: 11-2-2022 at 10:33:06

Strategy

Select Analysis Strategy: Combination (default)

Transition (2 Zones to 1 Zone) Criteria

Upper Layer Temperature ≥ 500 °C

Combustible in Upper Layer + U.L. Temperature ≥ Combustible Ignition Temperature = 300 °C

Interface Height ≤ 0,2 x Compartment Height

Fire Area ≥ 0,25 x Floor Area

Parameters

Openings

Radiation Through Closed Openings: 0,8

Bernoulli Coefficient: 0,7

Physical Characteristics of Compartment

Initial Temperature: 293 K

Initial Pressure: 100000 Pa

Parameters of Wall Material

Convection Coefficient at the Hot Surface: 35 W/m²K

Convection Coefficient at the Cold Surface: 9 W/m²K

Calculation Parameters

End of Calculation: 7200 sec

Time Step for Printing Results: 60 sec

Maximum Time Step for Calculation: 10 sec

Air Entrained Model:Heskestad

Temperature Dependent Openings

Temperature Dependent: 400 °C

Stepwise Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Linear Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Time Dependent Openings

Time	% of Total Openings
[sec]	[%]
0	5
1200	100

Compartment...

Compartment Geometry: Rectangular Floor

Height: 2,62 m

Depth: 10,8 m

Length: 10,8 m

Flat Roof

Floor

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6

Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Ceiling

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6
Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Wall 1

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 2

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 3

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 4

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Gypsum board [EN12524]	2,5	900	0,25	1000	0,8	0,8
Glass wool Rock wool	23,5	60	0,037	1030	0,8	0,8
EPS insulation	20	50	0,036	1300	0,6	0,6

Normal Bricks	0,4	1600	0,7	840	0,8	0,8

Openings

Sill Height Hi	Soffit Height Hs	Width	Variation	Adiabatic
[m]	[m]	[m]		
0,1	2,4	2,3	Constant	no
0,1	2,4	3	Constant	no
0,1	2,4	2,3	Constant	no

Fire...

Compartment Fire:: Annex E (EN 1991-1-2)

Max Fire Area: 116,64 m^2

Fire Elevation: 1 m

Fuel Height: 1,5 m

Occupancy	Fire Growth Rate	RHRf	Fire Load qf,k	Danger of Fire Activation
		[kW/m²]	80% Fractile [MJ/m²]	
User Defined	300	250	780	1

Active Fire Fighting Measures

Automatic Water Extinguishing System		δ_1=1
Independent Water Supplies		δ_2=1
Automatic Fire Detection by Heat		$\delta_{3,4}$=1
Automatic Fire Detection by Smoke		
Automatic Alarm Transmission to Fire Brigade		δ_5=1
Work Fire Brigade		$\delta_{6,7}$=1
Off Site Fire Brigade		
Safe Access Routes	on	δ_8=1
Staircases Under Overpressure in Fire Alarm		
Fire Fighting Devices	on	δ_9=1
Smoke Exhaust System	on	δ_{10}=1

Fire Risk Area: 12,5 m^2 $\delta_{q,1}$ = 1

Danger of Fire Activation:$\delta_{q,2}$ = 1

Active Measures:$\Pi\delta_{n,i}$ = 1

$q_{f,d}$ = 624,0

Combustion Heat of Fuel: 17,5MJ/kg

Combustion Efficiency Factor: 0,8

Combustion Model:External flaming

RESULTS

Fire Area: The maximum fire area (116.64m²) is greater than 25% of the floor area (116.64m²). The fire load is uniformly distributed.

Switch to one zone: Area of fire > 25.0% of floor area at time [s] 816.00

Fully engulfed fire: Temperature of zone in contact with fuel >300.0°C at time [s] 830.00

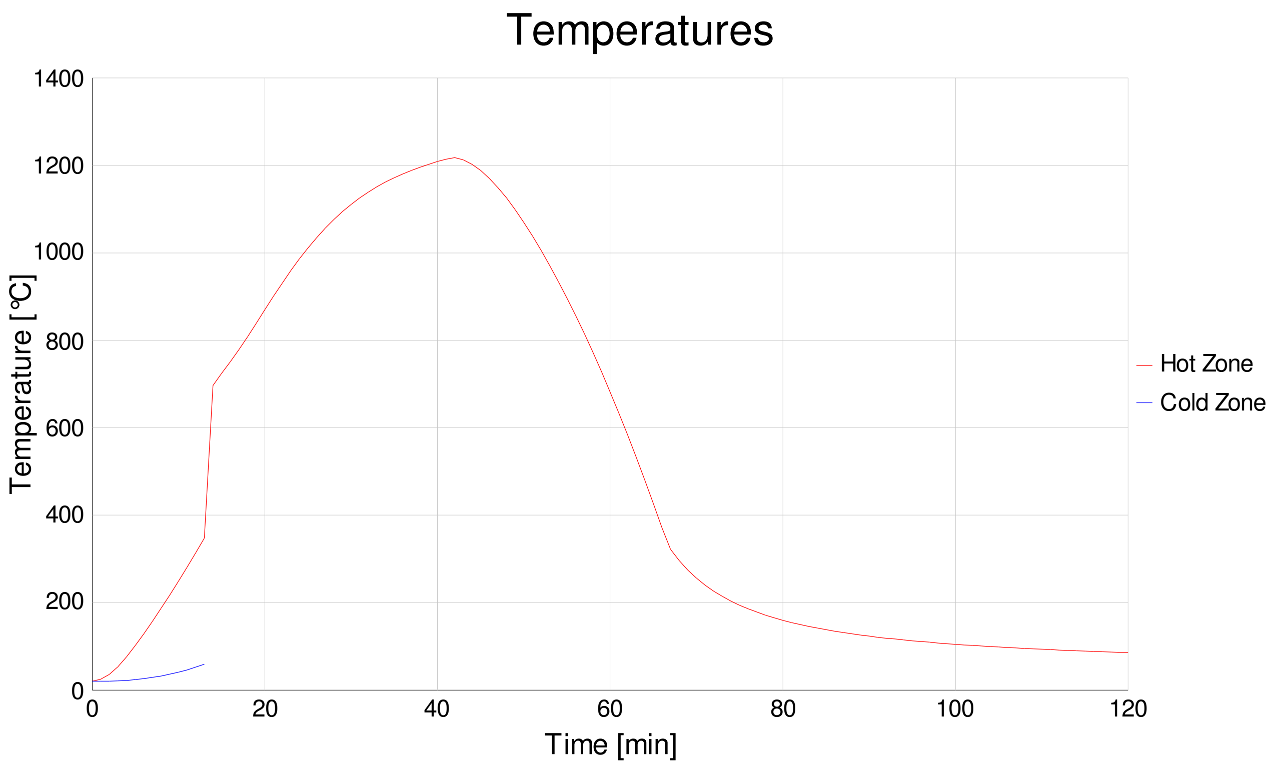

Figure 1. Hot and Cold Zone Temperature

Max: 1218°C At:42 min

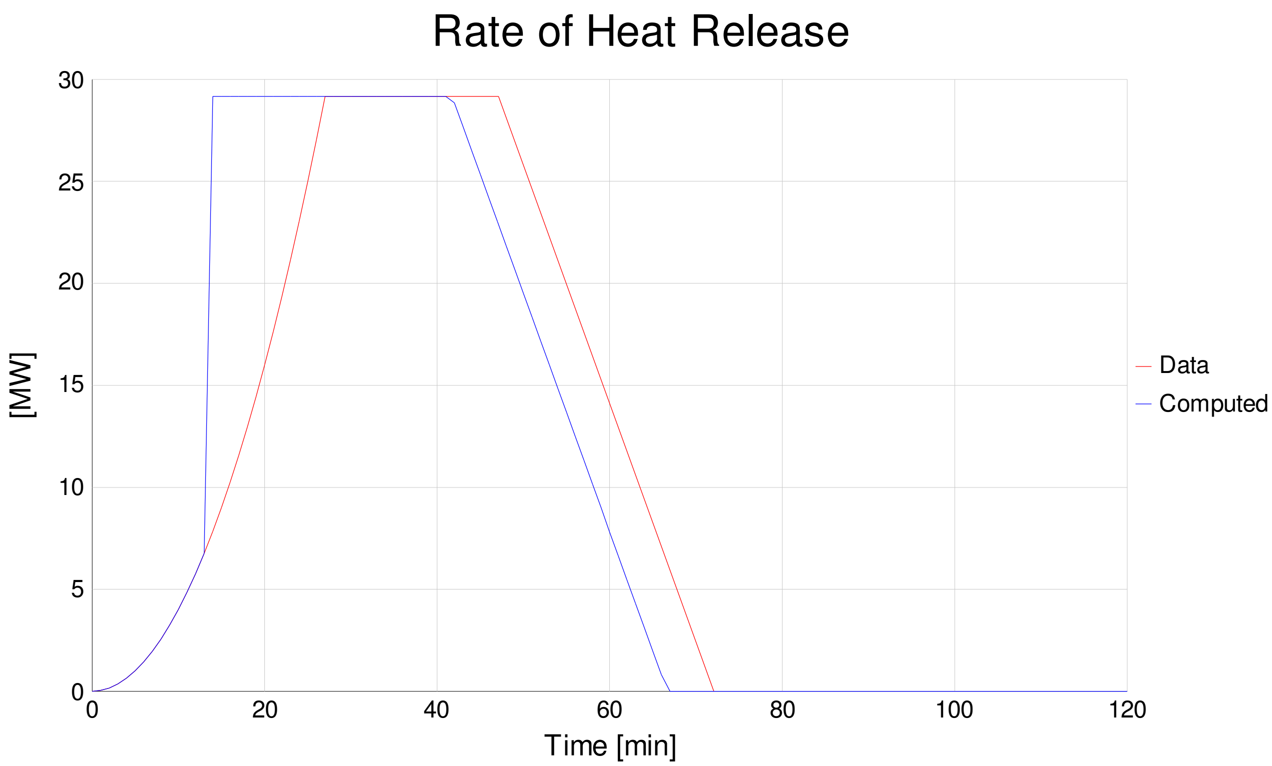

Figure 2. RHR Data and Computed

Max: 29,16MW At:27,0 min

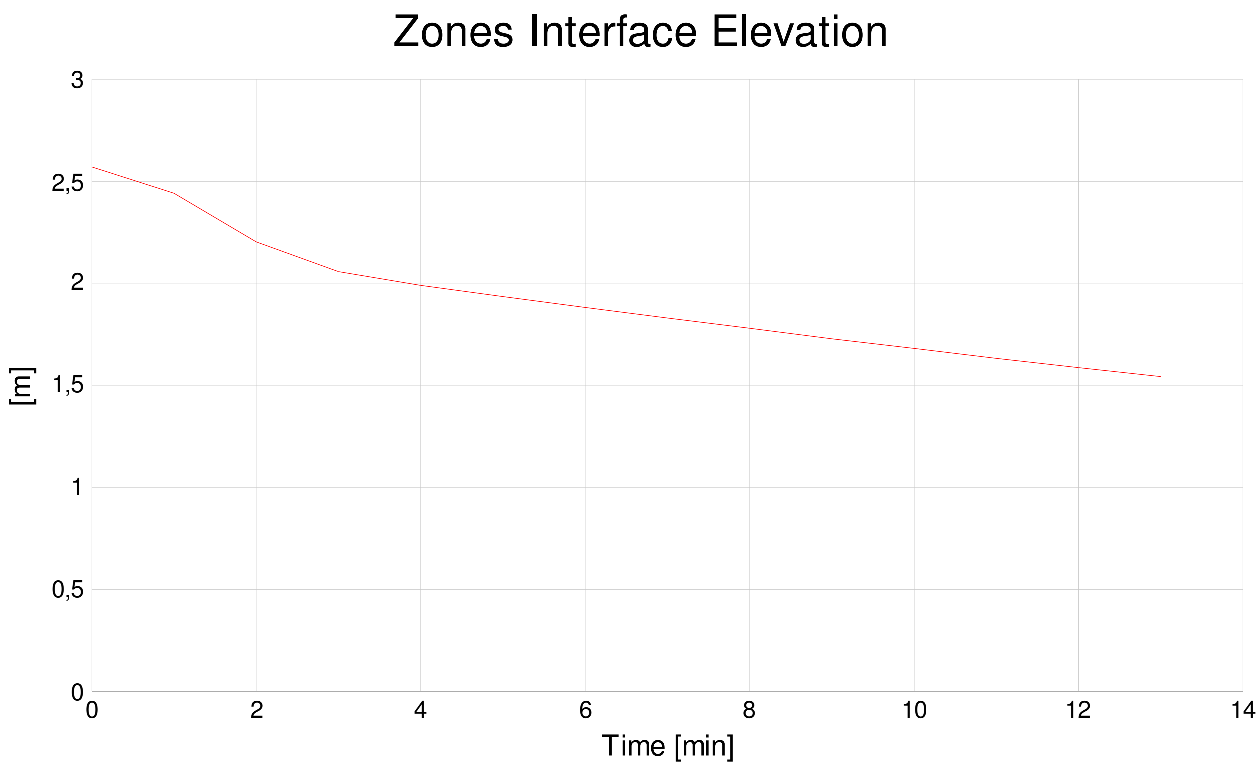

Figure 4. Zones Interface Elevation

Max: 1,54m At:13,00 min

Steel Profile...

Cross Section: Unprotected Cross Section

Steel Profile: IPE AA 80

Exposure: Exposed on Four Sides

Heating...

Profile Heated By: Hot Zone Temperature

Appendix F: OZone simulation of De Ananas | Scenario 1

OZone V 3.0.4 Report

ANALYSIS

Analysis Name:

File Name:C:\Users\s150415\Documents\1. Subjects\Q2. Masterproject II - fire safety\Case Ananas Higher RHRf.ozn

Created: 11-2-2022 at 11:10:48

Strategy

Select Analysis Strategy: Combination (default)

Transition (2 Zones to 1 Zone) Criteria

Upper Layer Temperature ≥ 500 °C

Combustible in Upper Layer + U.L. Temperature ≥ Combustible Ignition Temperature = 300 °C

Interface Height ≤ 0,2 x Compartment Height

Fire Area ≥ 0,25 x Floor Area

Parameters

Openings

Radiation Through Closed Openings: 0,8

Bernoulli Coefficient: 0,7

Physical Characteristics of Compartment

Initial Temperature: 293 K

Initial Pressure: 100000 Pa

Parameters of Wall Material

Convection Coefficient at the Hot Surface: 35 W/m²K

Convection Coefficient at the Cold Surface: 9 W/m²K

Calculation Parameters

End of Calculation: 7200 sec

Time Step for Printing Results: 60 sec

Maximum Time Step for Calculation: 10 sec

Air Entrained Model:Heskestad

Temperature Dependent Openings

Temperature Dependent: 400 °C

Stepwise Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Linear Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Time Dependent Openings

Time	% of Total Openings
[sec]	[%]
0	5
1200	100

Compartment...

Compartment Geometry: Rectangular Floor

Height: 2,62 m

Depth: 10,8 m

Length: 10,8 m

Flat Roof

Floor

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity

Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6
Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Ceiling

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6
Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Wall 1

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 2

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 3

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 4

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Gypsum board [EN12524]	2,5	900	0,25	1000	0,8	0,8

Glass wool Rock wool	23,5	60	0,037	1030	0,8	0,8
EPS insulation	20	50	0,036	1300	0,6	0,6
Normal Bricks	0,4	1600	0,7	840	0,8	0,8

Openings

Sill Height Hi	Soffit Height Hs	Width	Variation	Adiabatic
[m]	[m]	[m]		
0,1	2,4	2,3	Constant	no
0,1	2,4	3	Constant	no
0,1	2,4	2,3	Constant	no

Fire...

Compartment Fire:: Annex E (EN 1991-1-2)

Max Fire Area: 116,64 m^2

Fire Elevation: 1 m

Fuel Height: 1,5 m

Occupancy	Fire Growth Rate	RHRf	Fire Load qf,k	Danger of Fire Activation
		[kW/m²]	80% Fractile [MJ/m²]	
User Defined	300	375	780	1

Active Fire Fighting Measures

Automatic Water Extinguishing System		δ_1=1
Independent Water Supplies		δ_2=1
Automatic Fire Detection by Heat		$\delta_{3,4}$=1
Automatic Fire Detection by Smoke		
Automatic Alarm Transmission to Fire Brigade		δ_5=1
Work Fire Brigade		$\delta_{6,7}$=1
Off Site Fire Brigade		
Safe Access Routes	on	δ_8=1
Staircases Under Overpressure in Fire Alarm		
Fire Fighting Devices	on	δ_9=1
Smoke Exhaust System	on	δ_{10}=1

Fire Risk Area: 12,5 m^2 $\delta_{q,1}$ = 1

Danger of Fire Activation:$\delta_{q,2}$ = 1

Active Measures:$\Pi\delta_{n,i}$ = 1

$q_{f,d}$ = 624,0

Combustion Heat of Fuel: 17,5MJ/kg

Combustion Efficiency Factor: 0,8

Combustion Model:External flaming

RESULTS

Fire Area: The maximum fire area (116.64m²) is greater than 25% of the floor area (116.64m²). The fire load is uniformly distributed.

Switch to one zone + Fully engulfed fire: Temperature of zone >500.0°C at time [s] 970.00

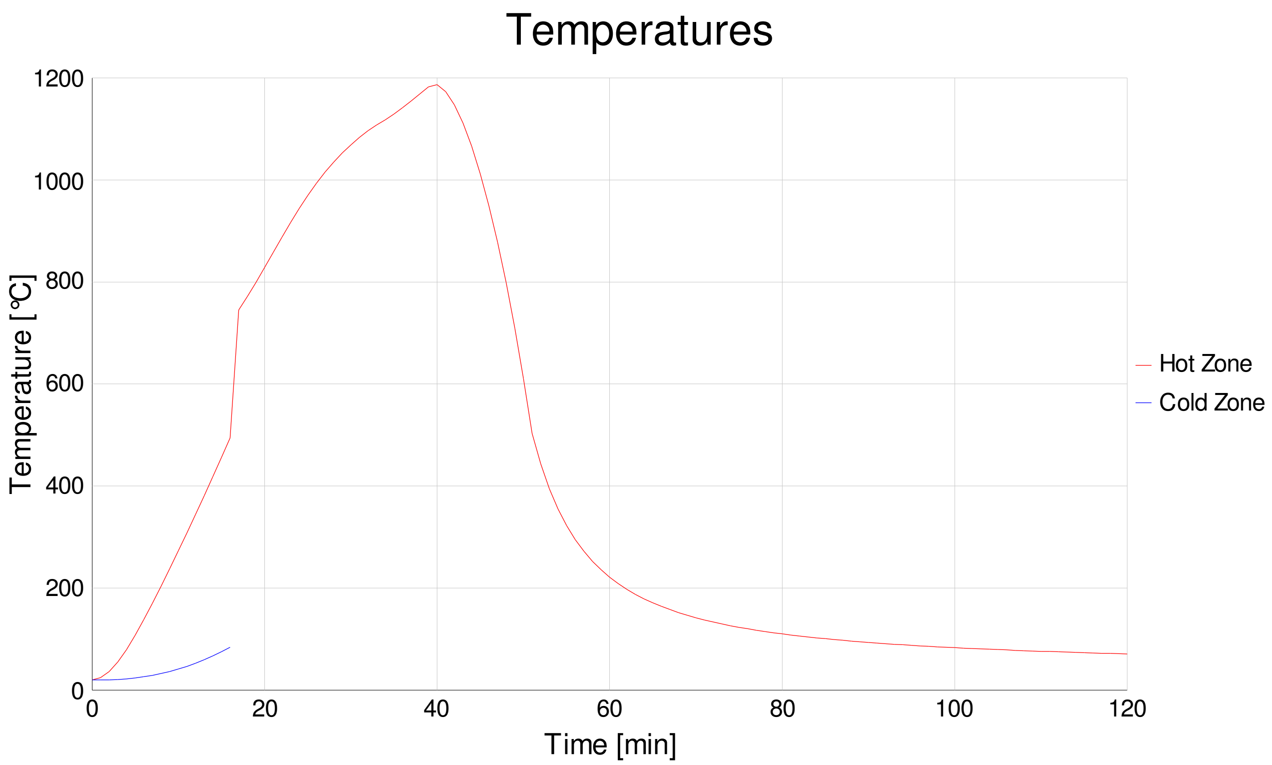

Figure 1. Hot and Cold Zone Temperature

Max: 1187°C At:40 min

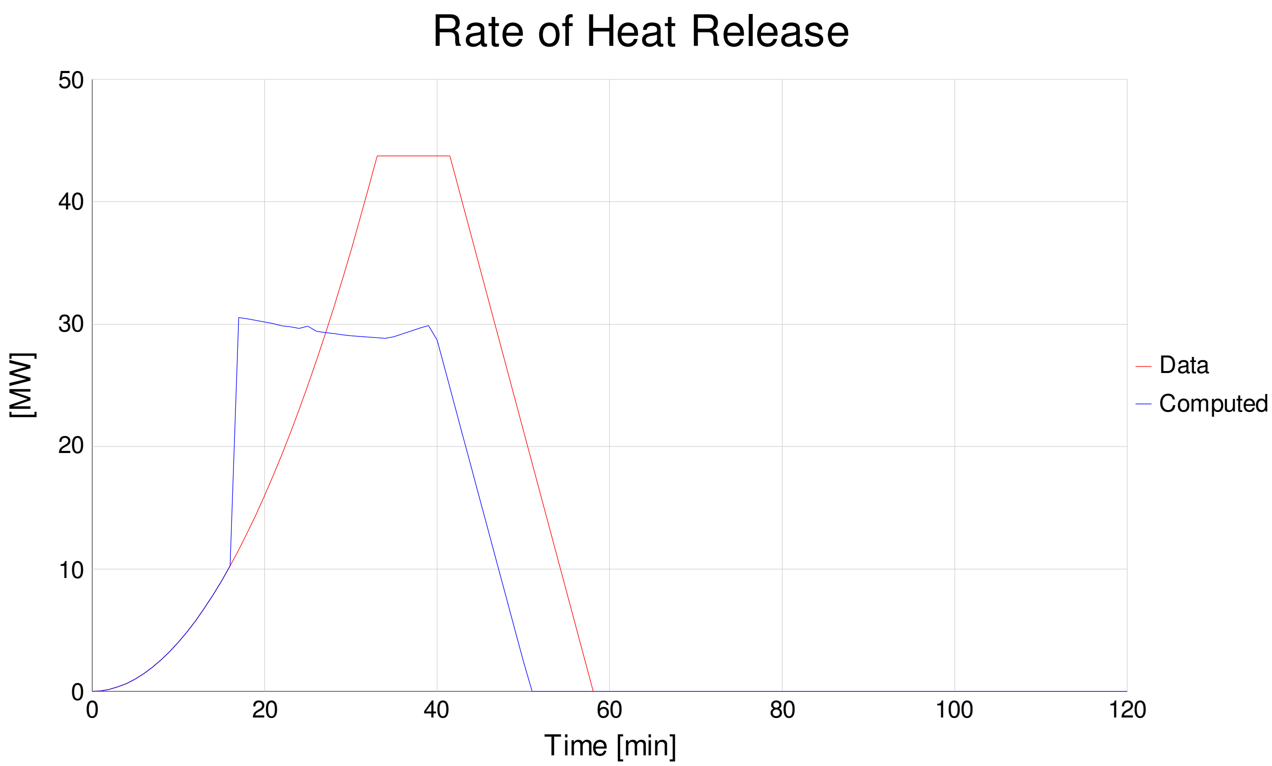

Figure 2. RHR Data and Computed

Max: 43,74MW At:33,1 min

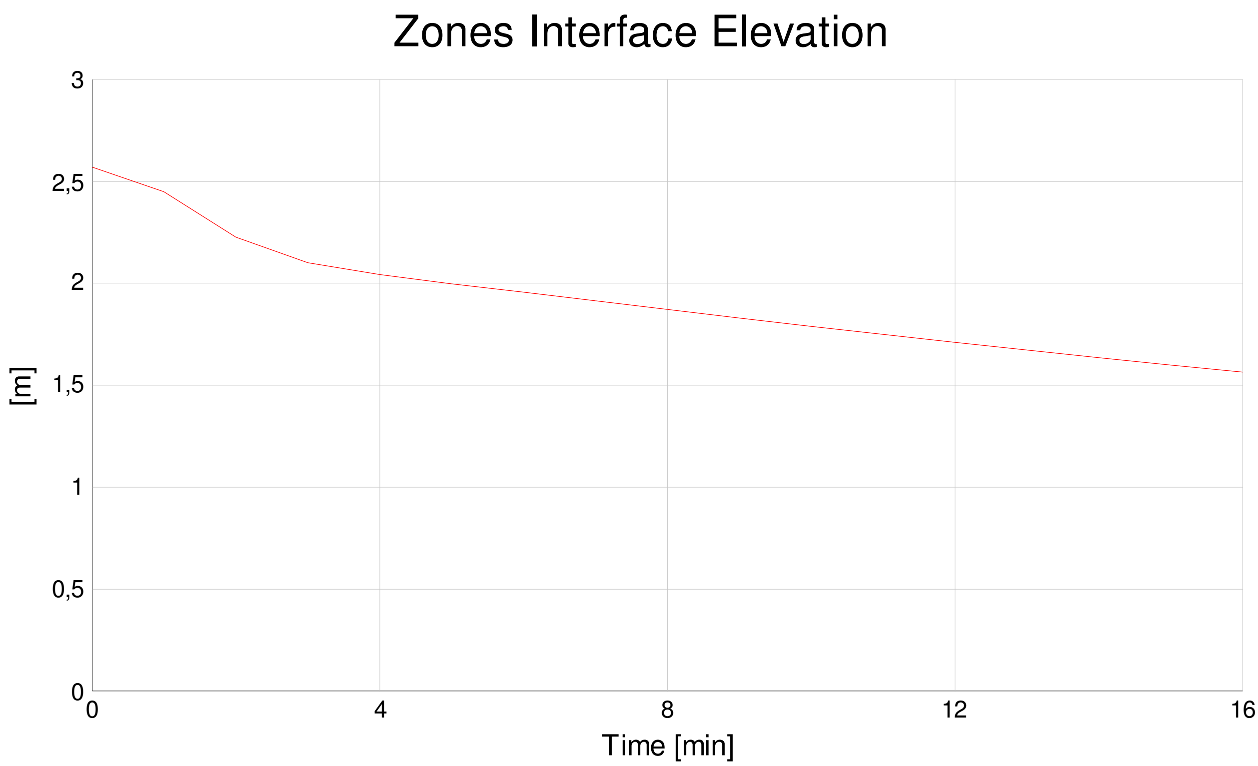

Figure 4. Zones Interface Elevation

Max: 1,57m At:16,00 min

Steel Profile...

Cross Section: Unprotected Cross Section

Steel Profile: IPE AA 80

Exposure: Exposed on Four Sides

Heating...

Profile Heated By: Hot Zone Temperature

Appendix G: OZone simulation of De Ananas | Scenario 2

OZone V 3.0.4 Report

ANALYSIS

Analysis Name:

File Name:C:\Users\s150415\Documents\1. Subjects\Q2. Masterproject II - fire safety\Case Ananas Higher Fire Load.ozn

Created: 11-2-2022 at 11:14:57

Strategy

Select Analysis Strategy: Combination (default)

Transition (2 Zones to 1 Zone) Criteria

Upper Layer Temperature ≥ 500 °C

Combustible in Upper Layer + U.L. Temperature ≥ Combustible Ignition Temperature = 300 °C

Interface Height ≤ 0,2 x Compartment Height

Fire Area ≥ 0,25 x Floor Area

Parameters

Openings

Radiation Through Closed Openings: 0,8

Bernoulli Coefficient: 0,7

Physical Characteristics of Compartment

Initial Temperature: 293 K

Initial Pressure: 100000 Pa

Parameters of Wall Material

Convection Coefficient at the Hot Surface: 35 W/m²K

Convection Coefficient at the Cold Surface: 9 W/m²K

Calculation Parameters

End of Calculation: 7200 sec

Time Step for Printing Results: 60 sec

Maximum Time Step for Calculation: 10 sec

Air Entrained Model:Heskestad

Temperature Dependent Openings

Temperature Dependent: 400 °C

Stepwise Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Linear Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Time Dependent Openings

Time	% of Total Openings
[sec]	[%]
0	5
1200	100

Compartment...

Compartment Geometry: Rectangular Floor

Height: 2,62 m

Depth: 10,8 m

Length: 10,8 m

Flat Roof

Floor

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity

Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6
Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Ceiling

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6
Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Wall 1

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 2

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 3

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 4

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Gypsum board [EN12524]	2,5	900	0,25	1000	0,8	0,8

Glass wool Rock wool	23,5	60	0,037	1030	0,8	0,8
EPS insulation	20	50	0,036	1300	0,6	0,6
Normal Bricks	0,4	1600	0,7	840	0,8	0,8

Openings

Sill Height Hi	Soffit Height Hs	Width	Variation	Adiabatic
[m]	[m]	[m]		
0,1	2,4	2,3	Constant	no
0,1	2,4	3	Constant	no
0,1	2,4	2,3	Constant	no

Fire...

Compartment Fire:: Annex E (EN 1991-1-2)

Max Fire Area: 116,64 m^2

Fire Elevation: 1 m

Fuel Height: 1,5 m

Occupancy	Fire Growth Rate	RHRf	Fire Load qf,k	Danger of Fire Activation
		[kW/m²]	80% Fractile [MJ/m²]	
User Defined	300	250	900	1

Active Fire Fighting Measures

Automatic Water Extinguishing System		δ_1=1
Independent Water Supplies		δ_2=1
Automatic Fire Detection by Heat		$\delta_{3,4}$=1
Automatic Fire Detection by Smoke		
Automatic Alarm Transmission to Fire Brigade		δ_5=1
Work Fire Brigade		$\delta_{6,7}$=1
Off Site Fire Brigade		
Safe Access Routes	on	δ_8=1
Staircases Under Overpressure in Fire Alarm		
Fire Fighting Devices	on	δ_9=1
Smoke Exhaust System	on	δ_{10}=1

Fire Risk Area: 12,5 m^2 $\delta_{q,1}$ = 1

Danger of Fire Activation:$\delta_{q,2}$ = 1

Active Measures:$\Pi\delta_{n,i}$ = 1

$q_{f,d}$ = 720,0

Combustion Heat of Fuel: 17,5MJ/kg

Combustion Efficiency Factor: 0,8

Combustion Model:External flaming

RESULTS

Fire Area: The maximum fire area ($116.64m^2$) is greater than 25% of the floor area ($116.64m^2$). The fire load is uniformly distributed.

Switch to one zone: Area of fire > 25.0% of floor area at time [s] 816.00

Fully engulfed fire: Temperature of zone in contact with fuel >300.0°C at time [s] 830.00

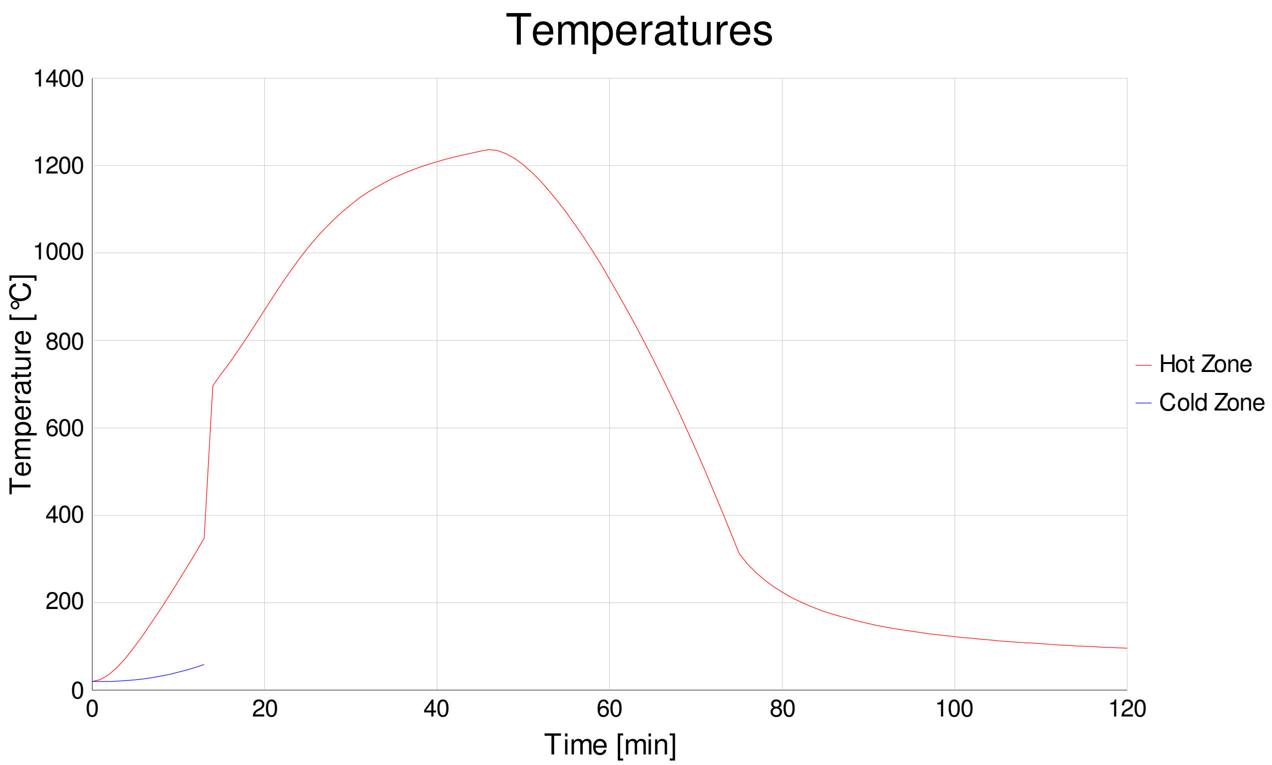

Figure 1. Hot and Cold Zone Temperature

Max: 1237°C At:46 min

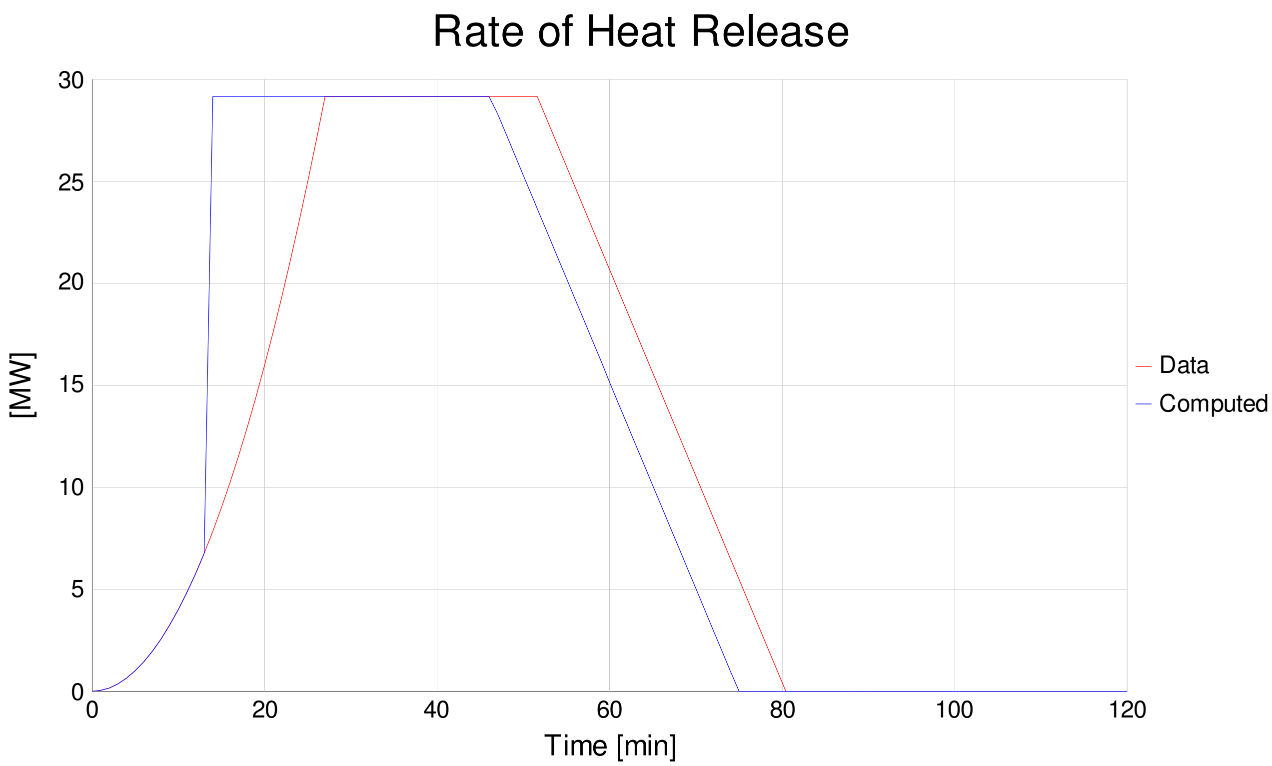

Figure 2. RHR Data and Computed

Max: 29,16MW At:27,0 min

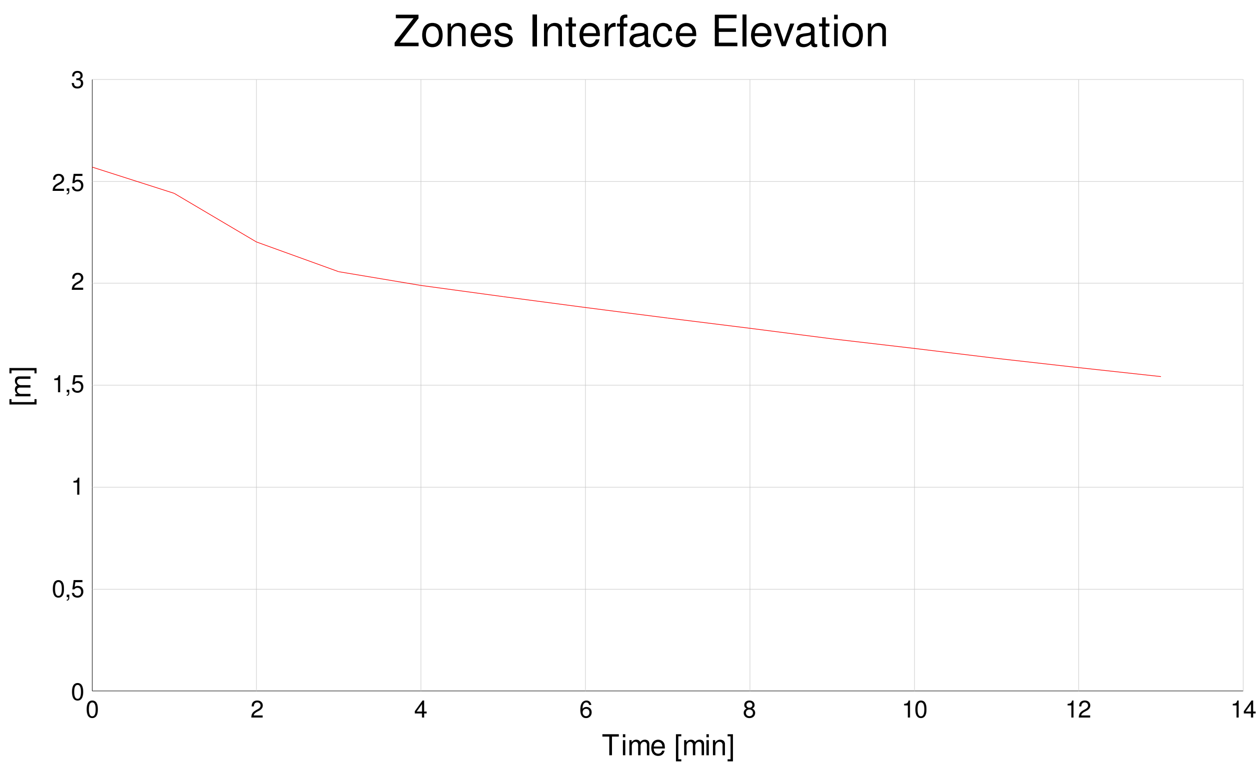

Figure 4. Zones Interface Elevation

Max: 1,54m At:13,00 min

Steel Profile...

Cross Section: Unprotected Cross Section

Steel Profile: IPE AA 80

Exposure: Exposed on Four Sides

Heating...

Profile Heated By: Hot Zone Temperature

Appendix H: OZone simulation of De Ananas | Scenario 3

OZone V 3.0.4 Report

ANALYSIS

Analysis Name:

File Name:C:\Users\s150415\Documents\1. Subjects\Q2. Masterproject II - fire safety\Case Ananas Fire Growth Rate.ozn

Created: 11-2-2022 at 11:17:31

Strategy

Select Analysis Strategy: Combination (default)

Transition (2 Zones to 1 Zone) Criteria

Upper Layer Temperature ≥ 500 °C

Combustible in Upper Layer + U.L. Temperature ≥ Combustible Ignition Temperature = 300 °C

Interface Height ≤ 0,2 x Compartment Height

Fire Area ≥ 0,25 x Floor Area

Parameters

Openings

Radiation Through Closed Openings: 0,8

Bernoulli Coefficient: 0,7

Physical Characteristics of Compartment

Initial Temperature: 293 K

Initial Pressure: 100000 Pa

Parameters of Wall Material

Convection Coefficient at the Hot Surface: 35 W/m²K

Convection Coefficient at the Cold Surface: 9 W/m²K

Calculation Parameters

End of Calculation: 7200 sec

Time Step for Printing Results: 60 sec

Maximum Time Step for Calculation: 10 sec

Air Entrained Model:Heskestad

Temperature Dependent Openings

Temperature Dependent: 400 °C

Stepwise Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Linear Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Time Dependent Openings

Time	% of Total Openings
[sec]	[%]
0	5
1200	100

Compartment...

Compartment Geometry: Rectangular Floor

Height: 2,62 m

Depth: 10,8 m

Length: 10,8 m

Flat Roof

Floor

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity

Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6
Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Ceiling

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6
Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Wall 1

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 2

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 3

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 4

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Gypsum board [EN12524]	2,5	900	0,25	1000	0,8	0,8

Glass wool Rock wool	23,5	60	0,037	1030	0,8	0,8
EPS insulation	20	50	0,036	1300	0,6	0,6
Normal Bricks	0,4	1600	0,7	840	0,8	0,8

Openings

Sill Height Hi	Soffit Height Hs	Width	Variation	Adiabatic
[m]	[m]	[m]		
0,1	2,4	2,3	Constant	no
0,1	2,4	3	Constant	no
0,1	2,4	2,3	Constant	no

Fire...

Compartment Fire:: Annex E (EN 1991-1-2)

Max Fire Area: 116,64 m^2

Fire Elevation: 1 m

Fuel Height: 1,5 m

Occupancy	Fire Growth Rate	RHRf	Fire Load qf,k	Danger of Fire Activation
		[kW/m²]	80% Fractile [MJ/m²]	
User Defined	150	250	780	1

Active Fire Fighting Measures

Automatic Water Extinguishing System		δ_1=1
Independent Water Supplies		δ_2=1
Automatic Fire Detection by Heat		$\delta_{3,4}$=1
Automatic Fire Detection by Smoke		
Automatic Alarm Transmission to Fire Brigade		δ_5=1
Work Fire Brigade		$\delta_{6,7}$=1
Off Site Fire Brigade		
Safe Access Routes	on	δ_8=1
Staircases Under Overpressure in Fire Alarm		
Fire Fighting Devices	on	δ_9=1
Smoke Exhaust System	on	δ_{10}=1

Fire Risk Area: 12,5 m^2 $\delta_{q,1}$ = 1

Danger of Fire Activation:$\delta_{q,2}$ = 1

Active Measures:$\Pi\delta_{n,i}$ = 1

$q_{f,d}$ = 624,0

Combustion Heat of Fuel: 17,5MJ/kg

Combustion Efficiency Factor: 0,8

Combustion Model:External flaming

RESULTS

Fire Area: The maximum fire area (116.64m²) is greater than 25% of the floor area (116.64m²). The fire load is uniformly distributed.

Switch to one zone: Area of fire > 25.0% of floor area at time [s] 406.85

Fully engulfed fire: Temperature of zone in contact with fuel >300.0°C at time [s] 430.00

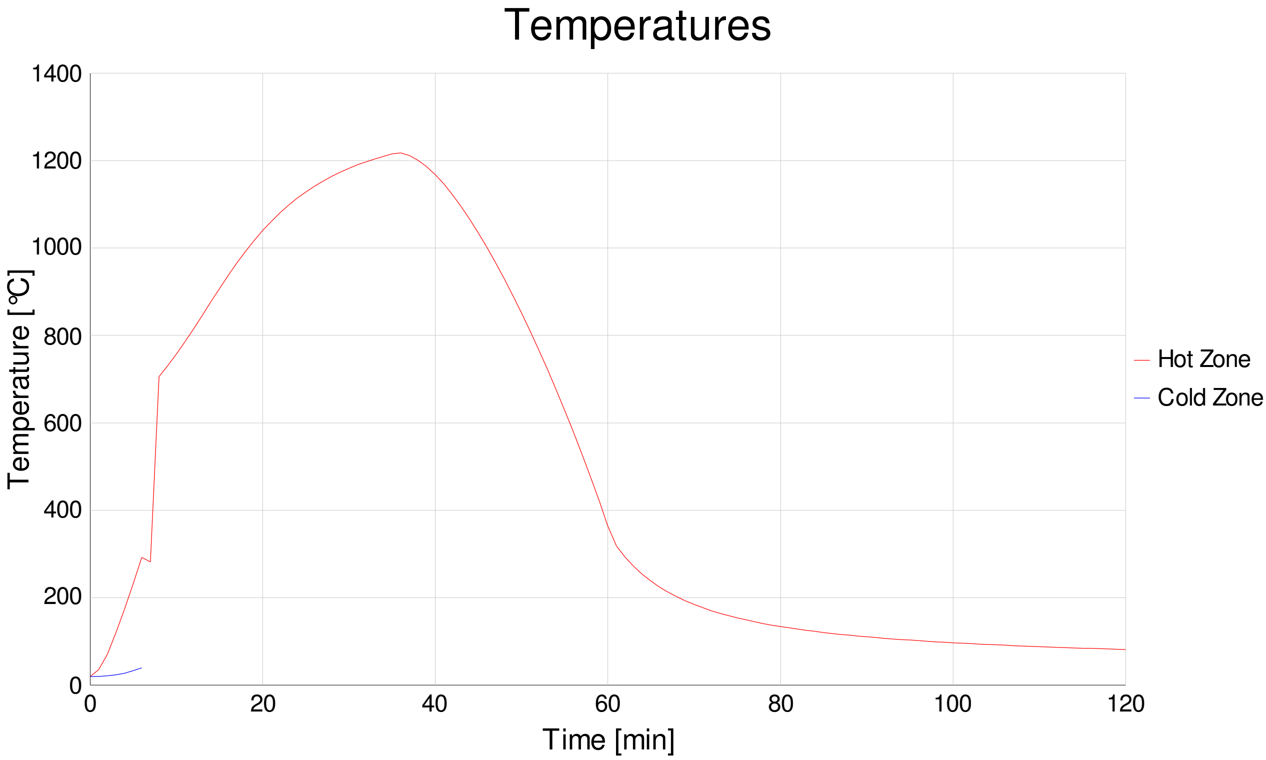

Figure 1. Hot and Cold Zone Temperature

Max: 1218°C At:36 min

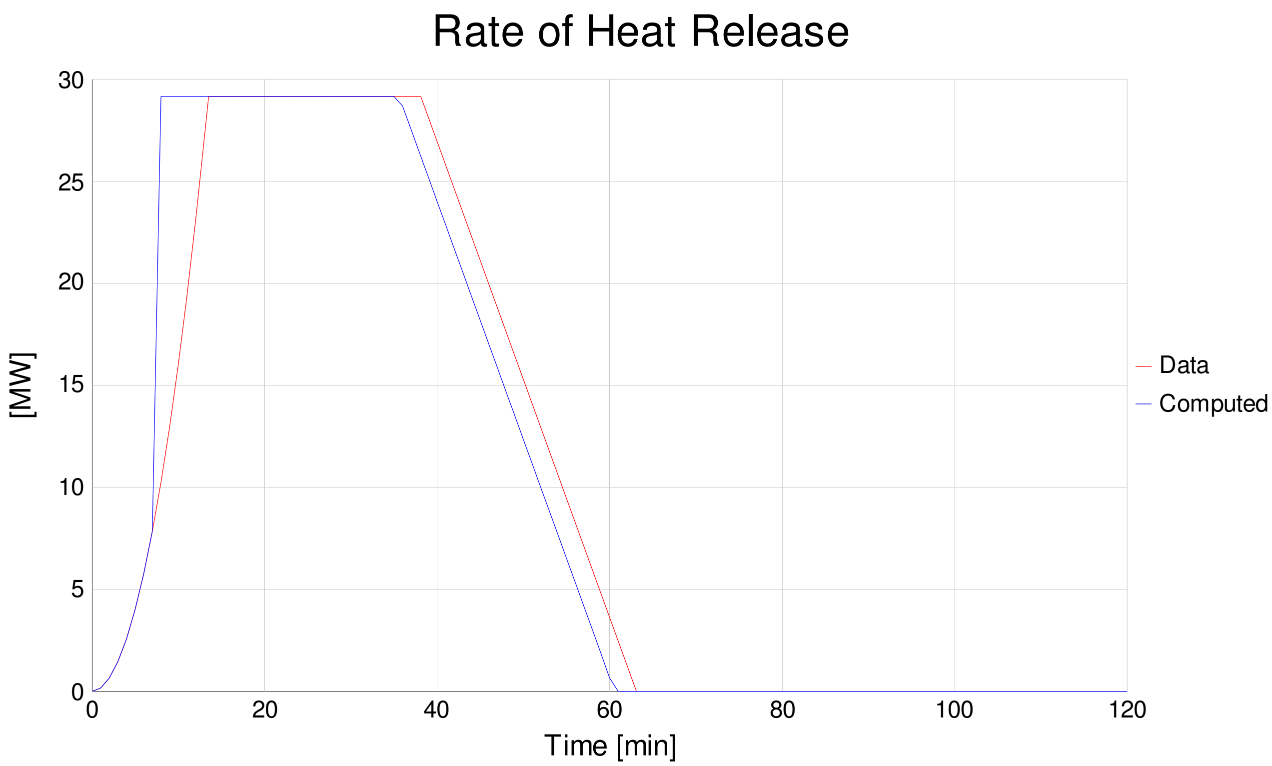

Figure 2. RHR Data and Computed

Max: 29,16MW At:13,5 min

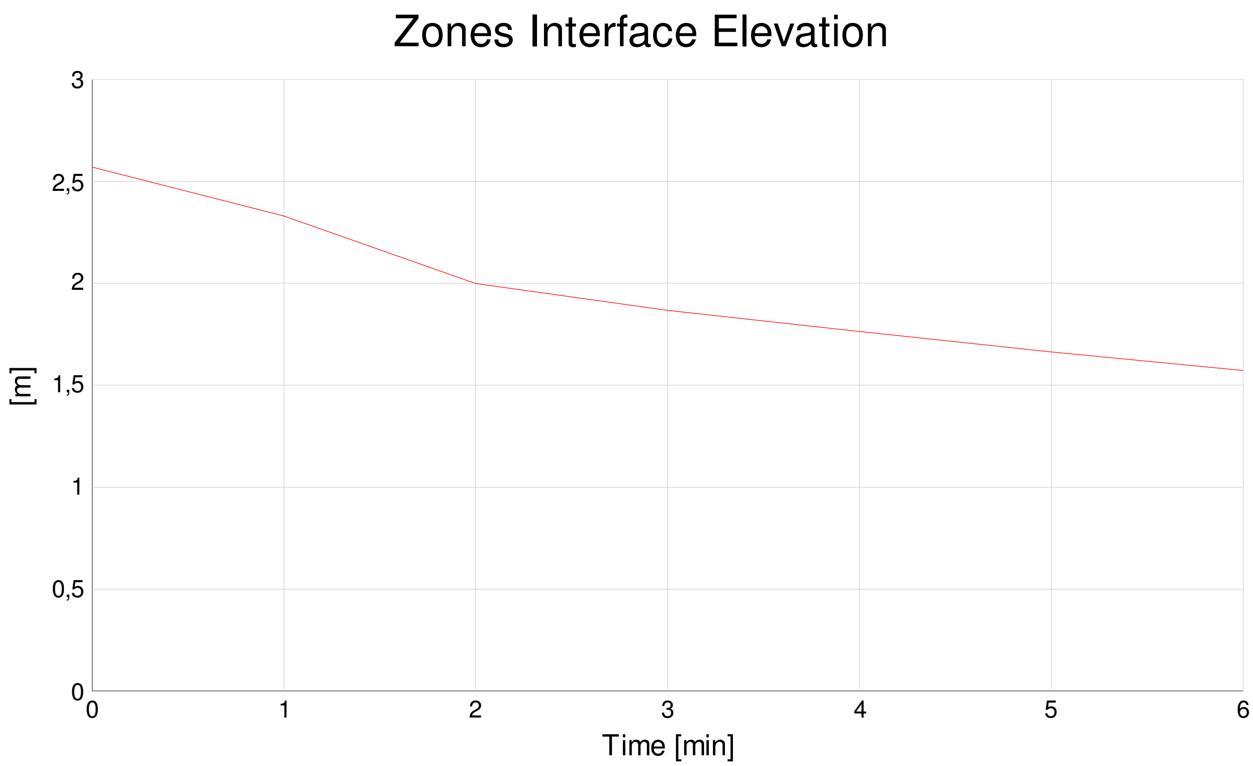

Figure 4. Zones Interface Elevation

Max: 1,57m At:6,00 min

Steel Profile...

Cross Section: Unprotected Cross Section

Steel Profile: IPE AA 80

Exposure: Exposed on Four Sides

Heating...

Profile Heated By: Hot Zone Temperature

Appendix I: OZone simulation of De Ananas | Scenario 4

OZone V 3.0.4 Report

ANALYSIS

Analysis Name:

File Name:C:\Users\s150415\Documents\1. Subjects\Q2. Masterproject II - fire safety\Case Ananas Two Openings.ozn

Created: 11-2-2022 at 10:37:58

Strategy

Select Analysis Strategy: Combination (default)

Transition (2 Zones to 1 Zone) Criteria

Upper Layer Temperature ≥ 500 °C

Combustible in Upper Layer + U.L. Temperature ≥ Combustible Ignition Temperature = 300 °C

Interface Height ≤ 0,2 x Compartment Height

Fire Area ≥ 0,25 x Floor Area

Parameters

Openings

Radiation Through Closed Openings: 0,8

Bernoulli Coefficient: 0,7

Physical Characteristics of Compartment

Initial Temperature: 293 K

Initial Pressure: 100000 Pa

Parameters of Wall Material

Convection Coefficient at the Hot Surface: 35 W/m²K

Convection Coefficient at the Cold Surface: 9 W/m²K

Calculation Parameters

End of Calculation: 7200 sec

Time Step for Printing Results: 60 sec

Maximum Time Step for Calculation: 10 sec

Air Entrained Model:Heskestad

Temperature Dependent Openings

Temperature Dependent: 400 °C

Stepwise Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Linear Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Time Dependent Openings

Time	% of Total Openings
[sec]	[%]
0	5
1200	100

Compartment...

Compartment Geometry: Rectangular Floor

Height: 2,62 m

Depth: 10,8 m

Length: 10,8 m

Flat Roof

Floor

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity

Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6
Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Ceiling

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6
Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Wall 1

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 2

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 3

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 4

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Gypsum board [EN12524]	2,5	900	0,25	1000	0,8	0,8

Glass wool Rock wool	23,5	60	0,037	1030	0,8	0,8
EPS insulation	20	50	0,036	1300	0,6	0,6
Normal Bricks	0,4	1600	0,7	840	0,8	0,8

Openings

Sill Height Hi	Soffit Height Hs	Width	Variation	Adiabatic
[m]	[m]	[m]		
0,1	2,4	2,3	Constant	no
0,1	2,4	3	Constant	no

Fire...

Compartment Fire:: Annex E (EN 1991-1-2)

Max Fire Area: 116,64 m^2

Fire Elevation: 1 m

Fuel Height: 1,5 m

Occupancy	Fire Growth Rate	RHRf	Fire Load qf,k	Danger of Fire Activation
		[kW/m²]	80% Fractile [MJ/m²]	
User Defined	300	250	780	1

Active Fire Fighting Measures

Automatic Water Extinguishing System		δ_1=1
Independent Water Supplies		δ_2=1
Automatic Fire Detection by Heat		$\delta_{3,4}$=1
Automatic Fire Detection by Smoke		
Automatic Alarm Transmission to Fire Brigade		δ_5=1
Work Fire Brigade		$\delta_{6,7}$=1
Off Site Fire Brigade		
Safe Access Routes	on	δ_8=1
Staircases Under Overpressure in Fire Alarm		
Fire Fighting Devices	on	δ_9=1
Smoke Exhaust System	on	δ_{10}=1

Fire Risk Area: 12,5 m^2 $\delta_{q,1}$ = 1

Danger of Fire Activation:$\delta_{q,2}$ = 1

Active Measures:$\Pi\delta_{n,i}$ = 1

$q_{f,d}$ = 624,0

Combustion Heat of Fuel: 17,5MJ/kg

Combustion Efficiency Factor: 0,8

Combustion Model:External flaming

RESULTS

Fire Area: The maximum fire area (116.64m²) is greater than 25% of the floor area (116.64m²). The fire load is uniformly distributed.

Switch to one zone + Fully engulfed fire: Temperature of zone in contact with fuel >300.0°C at time [s] 690.00

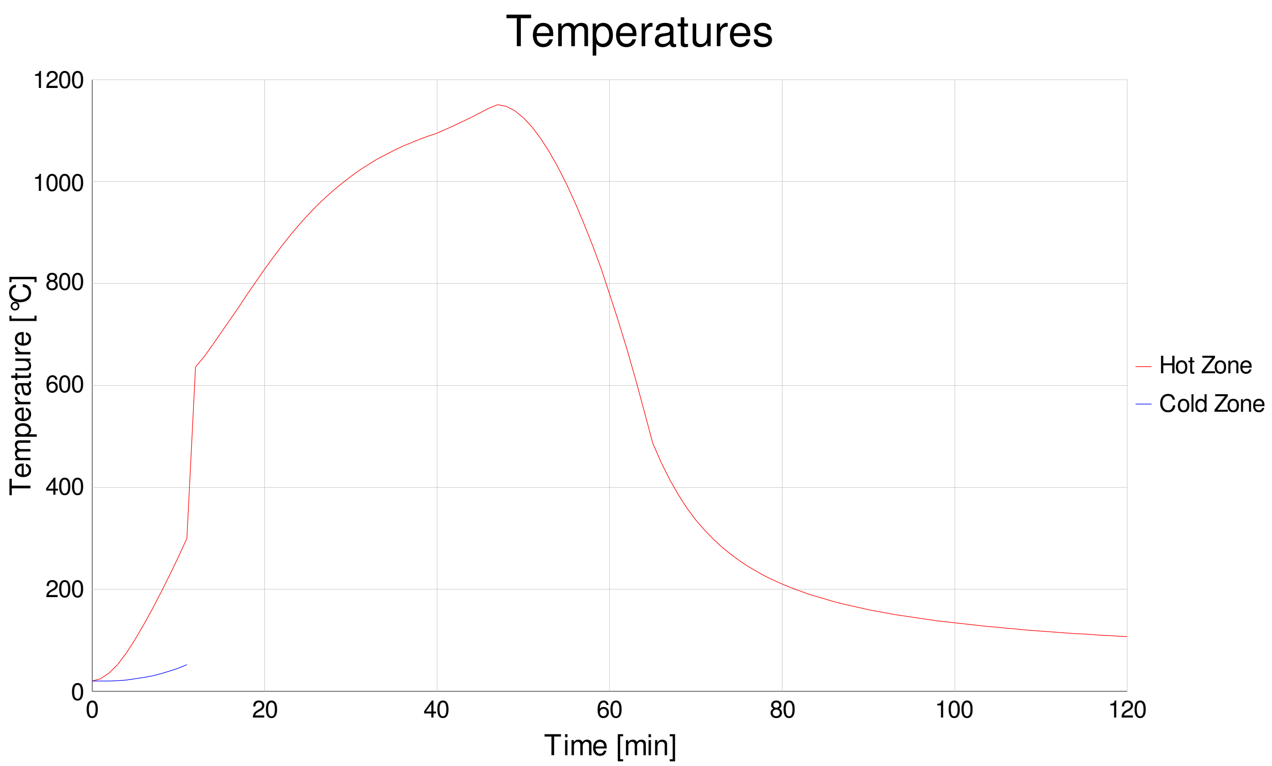

Figure 1. Hot and Cold Zone Temperature

Max: 1151°C At:47 min

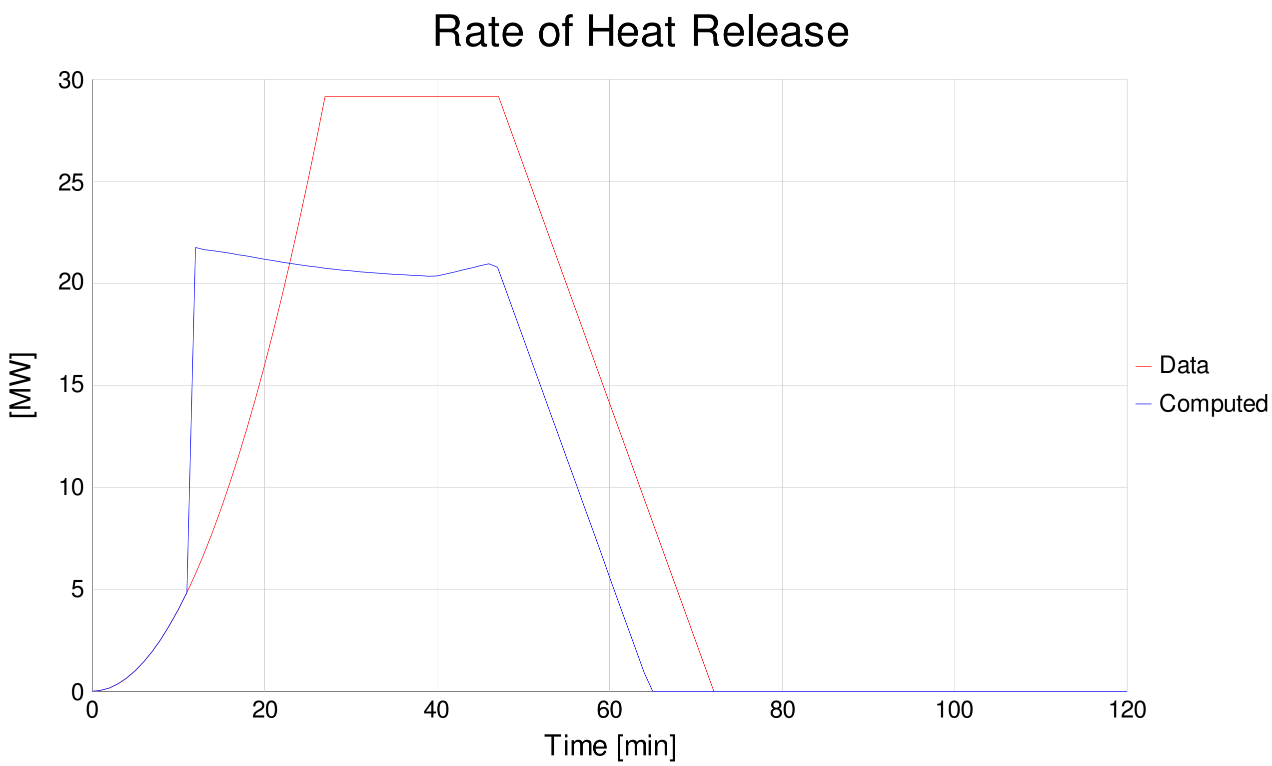

Figure 2. RHR Data and Computed

Max: 29,16MW At:27,0 min

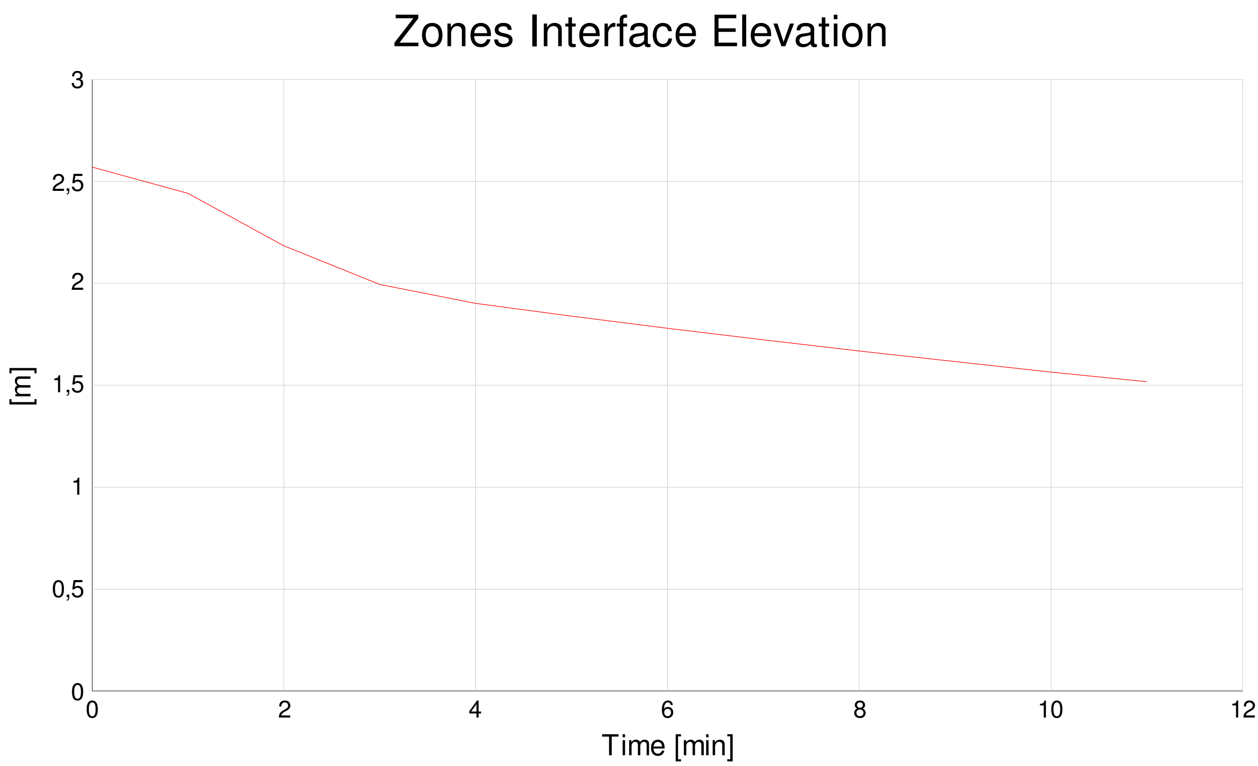

Figure 4. Zones Interface Elevation

Max: 1,52m At:11,00 min

Steel Profile...

Cross Section: Unprotected Cross Section

Steel Profile: IPE AA 80

Exposure: Exposed on Four Sides

Heating...

Profile Heated By: Hot Zone Temperature

Appendix J: OZone simulation of De Ananas | Scenario 5

OZone V 3.0.4 Report

ANALYSIS

Analysis Name:

File Name:C:\Users\s150415\Documents\1. Subjects\Q2. Masterproject II - fire safety\OZone files\Case Ananas One Opening.ozn

Created: 4-3-2022 at 14:16:16

Strategy

Select Analysis Strategy: Combination (default)

Transition (2 Zones to 1 Zone) Criteria

Upper Layer Temperature ≥ 500 °C

Combustible in Upper Layer + U.L. Temperature ≥ Combustible Ignition Temperature = 300 °C

Interface Height ≤ 0,2 x Compartment Height

Fire Area ≥ 0,25 x Floor Area

Parameters

Openings

Radiation Through Closed Openings: 0,8

Bernoulli Coefficient: 0,7

Physical Characteristics of Compartment

Initial Temperature: 293 K

Initial Pressure: 100000 Pa

Parameters of Wall Material

Convection Coefficient at the Hot Surface: 35 W/m²K

Convection Coefficient at the Cold Surface: 9 W/m²K

Calculation Parameters

End of Calculation: 7200 sec

Time Step for Printing Results: 60 sec

Maximum Time Step for Calculation: 10 sec

Air Entrained Model:Heskestad

Temperature Dependent Openings

Temperature Dependent: 400 °C

Stepwise Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Linear Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Time Dependent Openings

Time	% of Total Openings
[sec]	[%]
0	5
1200	100

Compartment...

Compartment Geometry: Rectangular Floor

Height: 2,62 m

Depth: 10,8 m

Length: 10,8 m

Flat Roof

Floor

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity

Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6
Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Ceiling

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Cement top floor	7	1440	0,29	920	0,54	0,54
EPS_T insulation	3	50	0,03	1200	0,6	0,6
Normal weight Concrete [EN1994-1-2]	26	2300	1,6	1000	0,8	0,8

Wall 1

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 2

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 3

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1,6	1000	0,8	0,8

Wall 4

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Gypsum board [EN12524]	2,5	900	0,25	1000	0,8	0,8

Glass wool Rock wool	23,5	60	0,037	1030	0,8	0,8
EPS insulation	20	50	0,036	1300	0,6	0,6
Normal Bricks	0,4	1600	0,7	840	0,8	0,8

Fire...

Compartment Fire:: Annex E (EN 1991-1-2)

Max Fire Area: 116,64 m^2

Fire Elevation: 1 m

Fuel Height: 1,5 m

Occupancy	Fire Growth Rate	RHRf	Fire Load qf,k	Danger of Fire Activation
		[kW/m²]	80% Fractile [MJ/m²]	
User Defined	300	250	780	1

Active Fire Fighting Measures

Automatic Water Extinguishing System		δ_1=1
Independent Water Supplies		δ_2=1
Automatic Fire Detection by Heat		$\delta_{3,4}$=1
Automatic Fire Detection by Smoke		
Automatic Alarm Transmission to Fire Brigade		δ_5=1
Work Fire Brigade		$\delta_{6,7}$=1
Off Site Fire Brigade		
Safe Access Routes	on	δ_8=1
Staircases Under Overpressure in Fire Alarm		
Fire Fighting Devices	on	δ_9=1
Smoke Exhaust System	on	δ_{10}=1

Fire Risk Area: 12,5 m^2 $\delta_{q,1}$ = 1

Danger of Fire Activation:$\delta_{q,2}$ = 1

Active Measures:$\Pi\delta_{n,i}$ = 1

$q_{f,d}$ = 624,0

Combustion Heat of Fuel: 17,5MJ/kg

Combustion Efficiency Factor: 0,8

Combustion Model:External flaming

RESULTS

Fire Area: The maximum fire area (116.64m²) is greater than 25% of the floor area (116.64m²). The fire load is uniformly distributed.

Switch to one zone + Fully engulfed fire: Temperature of zone in contact with fuel >300.0°C at time [s] 620.00

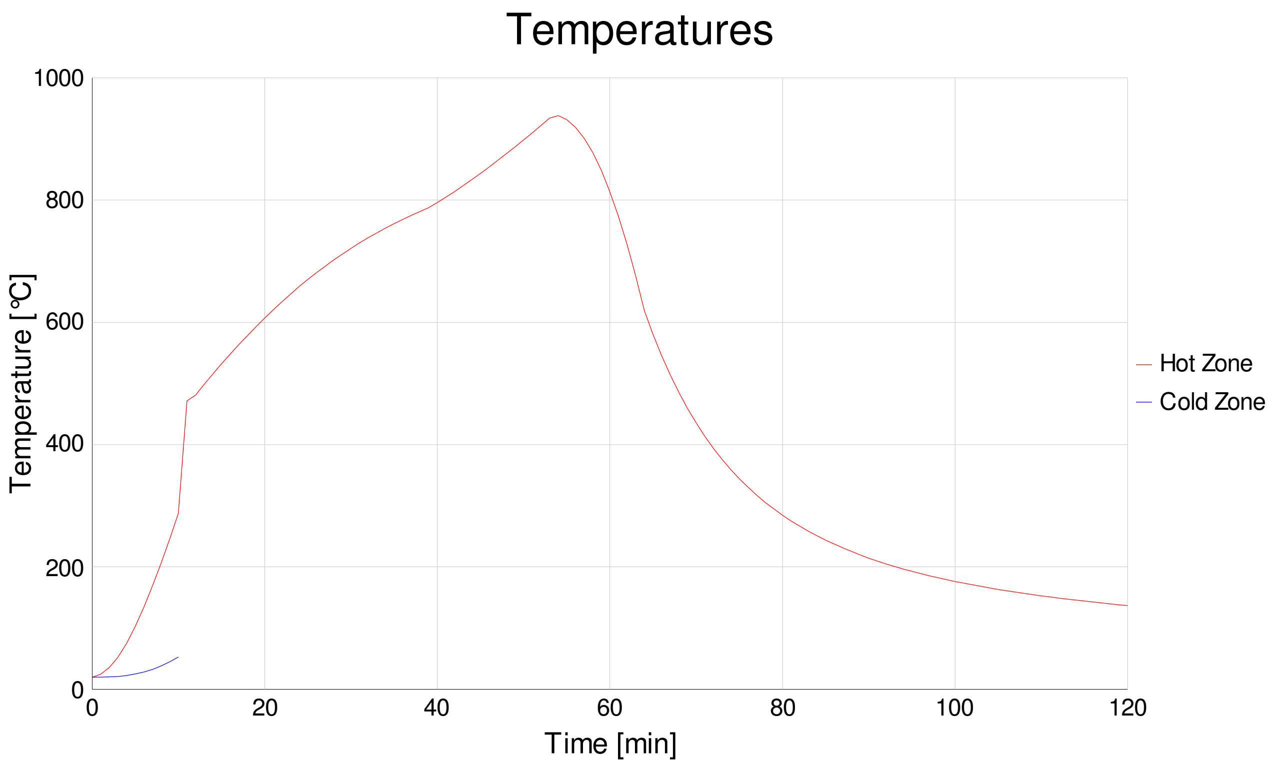

Figure 1. Hot and Cold Zone Temperature

Max: 938°C At:54 min

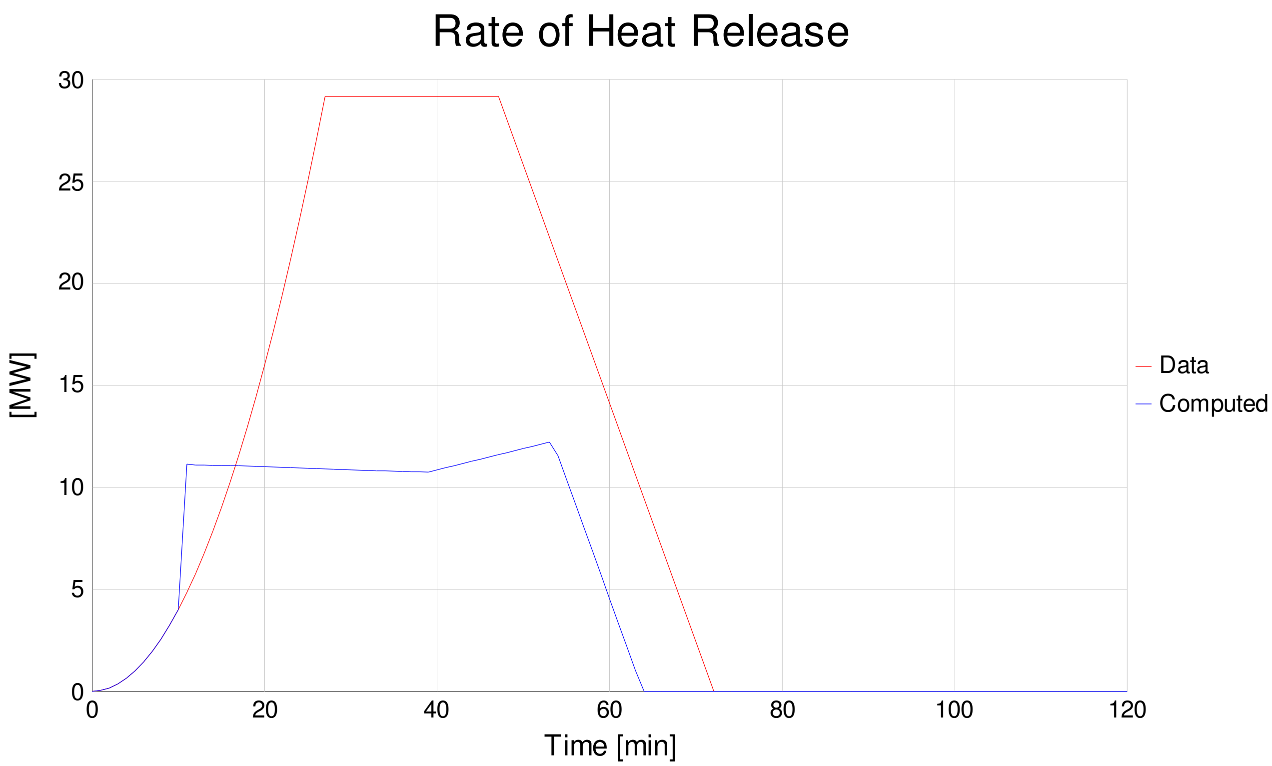

Figure 2. RHR Data and Computed

Max: 29,16MW At:27,0 min

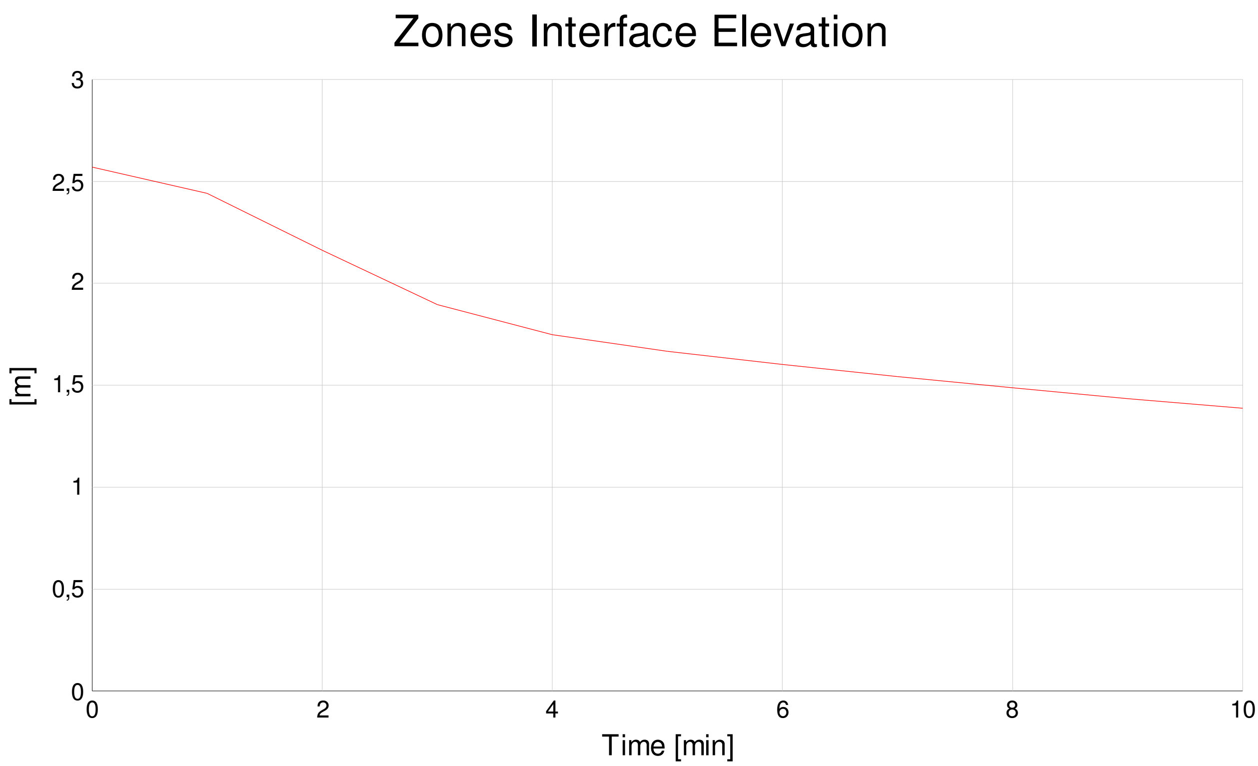

Figure 4. Zones Interface Elevation

Max: 1,39m At:10,00 min

Steel Profile...

Cross Section: Unprotected Cross Section

Steel Profile: IPE AA 80

Exposure: Exposed on Four Sides

Heating...

Profile Heated By: Hot Zone Temperature

Appendix K: OZone simulation of De Ananas | Probabilistic approach

PROBABILISTIC APPROACH RHR EXTERNAL FLAMES

Ozone natural fire simulations
Sensitivity analysis
CASE: Ananas Leiden

SENSITIVITY ANALYSIS RHR(ext)
stochastic boundary conditions

scenario			unit	deterministic: average x	deterministic: t [MW]
2	**q**	fire load density	MJ/m^2	780	
1	**RHR**	rate of heat release density	kW/m2	250	
4	**Aopen/A**	openings	%	100	
3	**tc**	timeconstant fire development	s	300	
		RHR(ext) in average conditions	MW	**RHR**	**-1,3**

probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	RHR t [MW]
0,15	120	900	-1,3
0,50	125	375	13,2
-0,30	-30,00	70,00	8,7
-0,50	-150,00	150,00	-1,3

standard deviation		
dt/dx	s·dt/dx	(s·dt/dx)^2
0,00	0,00	0,00
0,12	14,50	210,25
-0,33	10,00	100,00
0,00	0,00	0,00
	variancy(t) =	310,250
	s(t) =	17,614

reliability and cumulative probability
RHR(ext)

t [MW]	s(t)	beta(t|fi)	p(t|fi)
0	17,61391	0,074	5,29E-01
0,03	17,61391	0,076	5,30E-01
0,23	17,61391	0,087	5,35E-01
5	17,61391	0,358	6,40E-01
10	17,61391	0,642	7,39E-01
15	17,61391	0,925	8,226E-01
20	17,61391	1,209	8,87E-01
25	17,61391	1,493	9,32E-01
30	17,61391	1,777	9,62E-01
35	17,61391	2,061	9,80E-01
40	17,61391	2,345	9,90E-01
45	17,61391	2,629	9,96E-01
50	17,61391	2,912	9,98E-01
55	17,61391	3,196	9,99E-01
60	17,61391	3,480	1,00E+00
65	17,61391	3,764	1,00E+00
70	17,61391	4,048	1,00E+00
75	17,61391	4,332	1,00E+00
80	17,61391	4,616	1,00E+00
85	17,61391	4,900	1,00E+00