PREFACE

This document is prepared as a Polish presentation for Case Study No. 2 – Production and Storage Building, and prepared by employees of Building Research Institute (ITB), who are members of Polish Chapter of SFPE.

This document contains proposals for technical solutions in a hypothetical building, described in following chapters. The objective of production and storage case study was to demonstrate common difficulties encountered in performance based design involving industrial or storage buildings.

The proposed strategy does follow SFPE recommendations, and does focus on following fire and life safety goals:
1. Safeguard occupants from injury due to fire and smoke until they reach a safe place.
2. Safeguard fire fighters while performing rescue operations or attacking the fire.
3. Minimize smoke and fire spread inside building.
4. Limit the impact on business continuity

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1 INTRODUCTION

Modern industrial buildings often have multiple purpose, underneath the same roof. It is often a case for logistic/production centres to be a raw material warehouse, production line and product storage at the same time. Design of such buildings brings more challenges than just a single purpose storage or production facility – it requires a lot of attention to the subdivision into zones by the designer, but also at later stage, as much attention by the owner to maintain this division. Engineered solutions for storage may not be applicable in the manufacturing area, and otherwise.

In Poland, the main source of regulation for buildings is the Technical-Building Requirements [1]. This act of law regulates basic architectural parameters of the building, such as firestop partitions, sizing of zones, evacuation requirements and basic requirements for technical installations. Second important act of law is the Requirements of Fire Safety [2], which regulate features of the building important to the fire signalling and firefighting. Where Technical Requirements are not detailed enough about the solution considered, the designer must use so called “State of the Art” technical knowledge, which can often be related to Polish or foreign standards, peer reviewed papers or handbooks such as SFPE Handbook of Fire Protection Engineering [5].

Three categories of requirements and approach to them can be described:

1. requirements that are coming straight from the act of law (fully prescriptive) and have a single value;
2. requirements that are put in tables – this is a prescriptive way of design, but allows for some decisions that might heavily alter the requirement (ie. choosing to secure the building with sprinklers or not);
3. requirements for smoke exhaust system that may be considered fully performance based design as only expected effect of the use of such system is mentioned. This requires performance analysis of evacuation, fire growth etc.

It is possible to not use performance methods for 3), and use Polish standards instead (which we would not recommend, but it can be seen in some design in our country). When preparing a design for the building permit, the architect together with a Fire Expert have to prepare a document Fire Safety Requirements (Warunki Ochrony Przeciwpożarowej) and a Fire Scenario, in which most of the features of fire safety have to be included. These documents contain all
design choices, references to acts of law, standards and other sources of technical knowledge used in the design process.

In production and storage facilities, it is important to assess if there are zones of explosion risk in the building – if there are any, most of the requirements are much higher. **For the sake of this case study, it is determined that there is no explosion risk zone within the building, further in the document some basic requirements for analysis that should be performed are shown.**

As the requirements are given for a particular way of use of the fire zone, it cannot be changed without a new building permit, in a way that would cause a change in the requirements to this zone. This is especially difficult when a law is updated, as then building may not meet the new regulations. There is a possible derogation way for this event – but only for existing structures that are altered, modified, overbuilt or their use is altered.

2 SHORT DESCRIPTION OF THE BUILDING

The structure is a large speculative logistics building. The total dimensions of the building are 180 x 100 m, and the height of the building from the floor to the ceiling is 12 m. The building is divided into three equal tenant spaces, separated with compartment walls.

The tenant spaces involve various types of production and storage activities, show on Figure 1.

Each of the tenants areas have different storage or production facilities, that are as follows:
- Tenant 1 – High bay storage with 2 levels of cat-walks at levels of 4 and 8 m (document archive), additional office mezzanine above loading bay;
- Tenant 2 – High bay storage with man-up system (car parts warehouse);
- Tenant 3 – Production of furniture with raw material storage and ready products storage, 2 floor office building.

Fig. 1. Tenant spaces within the building
Fig. 2. Visual concept of the hypothetical logistics centre
3 PERFORMANCE ENGINEERING OF INDUSTRIAL BUILDINGS IN POLAND

3.1 Law requirements

The Technical-Building Requirements give basic requirements regarding the building, that have to be met by the designer. This requirements, are similar to the requirements written in Appendix 1 to EU CPR 305/2011, and are placed in §207 of [1]:

The construction works must be designed and built in such a way that in the event of an outbreak of fire:

(a) the load-bearing capacity of the construction can be assumed for the time appointed in the Act;
(b) the generation and spread of fire and smoke within the construction works are limited;
(c) the spread of fire to neighbouring construction works is limited;
(d) occupants can leave the construction works;
(e) the safety of rescue teams is taken into consideration.

This paragraph is sometimes treated as a performance requirement, but when treating with point a) it is often considered an abuse to go with just load-bearing analysis. Reader must be warned, that §216 [1] requires from the structure to be qualified in a class of Fire Resistance, which is related to standard time-temperature curve, and using ie. parametric or localized fire based on Eurocode may not lead to obtaining this.

The requirements of the document (with the sole exception of SHEVS) are strictly prescriptive based, and are dependent on simple tabularised risk assessment methods. It is possible to omit these requirements when applying a project for a new building, as written in higher level act [3] – The Building Law Act §9.1. This route is a derogation route, which means that the Ministry of Building and Transportation has to allow to meet the requirements in a different way, than described in [1]. The application for derogation has to show detailed information about the proposed alteration in the design, and show the results in comparison with the original design. The performance engineering methods are widely used for the purpose of obtaining various derogations, although it must be noted, that this procedure takes a lot of time, and the construction works cannot start before the derogation is issued and building permit is obtained.

The only performance engineering requirement written straight into the [1], is the requirement for Smoke And Heat Ventilation Systems – in §270:

“Smoke and heat ventilation system should (...) remove the smoke with efficiency that assures, that in time required to evacuate people on passages and evacuation roads there will not be smoke or temperature, that will make the safe evacuation impossible”

Although no regulations are given of what is the way to estimate the time required to evacuate people or what are the conditions that make the safe evacuation impossible, this paragraph is interpreted as straightforward implementation of ASET>RSET rule, as in many different parts of the world. It must be noted, that RSET calculations are usually performed following the
requirements of PD 7974-6 [4], although Polish technical requirements are very different, than ones required by BS 9999 and other British regulations.

### 3.2 Engineering methods used

In some design aspects, the performance engineering methods may be used as mentioned before state of art technical knowledge. The “short list” of methods popular in Poland is presented in Table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Software / model</th>
<th>Popularity</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD</td>
<td>FDS, ANSYS, Phoenix, Smartfire, AutodeskCFD</td>
<td>medium</td>
<td>CFD analysis form the base of most of SHEV design, are widely used in evaluation of environmental conditions for users. Often referred as the valid method for estimation of ASET time, for the purpose of §270.1 [1] In industrial buildings, AHJ often respects hand calculations without additional simulations.</td>
</tr>
<tr>
<td>Evacuation</td>
<td>Pathfinder, Evac, buildingExodus</td>
<td>medium</td>
<td>Usually combined with CFD analysis as the method for estimation of RSET</td>
</tr>
<tr>
<td>Hand calculations</td>
<td>Fire Load Density</td>
<td>high</td>
<td>Requirements for industrial buildings rely on Fire Load Density, thus this element is part of every industrial design</td>
</tr>
<tr>
<td></td>
<td>Explosion Risk</td>
<td>high</td>
<td>Risk of explosion will increase the requirements for the building</td>
</tr>
<tr>
<td></td>
<td>Sizing SHEVS – NFPA, PB, DIN, TR, fireplatform.eu</td>
<td>high</td>
<td>Hand calculations are always part of the SHEVS design, and often the only dimensioning approach used</td>
</tr>
<tr>
<td></td>
<td>RTI calculations</td>
<td>medium</td>
<td>Used in the assessment of sprinkler/vent interaction and sizing of the design fire</td>
</tr>
<tr>
<td>Zone Modeling</td>
<td>CFAST, Brisk, fireplatform.eu</td>
<td>low</td>
<td>Used in some preliminary design, rarely part of the building design permit application</td>
</tr>
<tr>
<td>Radiation modeling</td>
<td>fireplatform.eu, FDS, ANSYS</td>
<td>low</td>
<td>Used in the derogation process for the possible separation between the buildings, may be used for the design of separation between storage areas in storage facility</td>
</tr>
<tr>
<td>FEM/FVM</td>
<td>ANSYS, Robot</td>
<td>low</td>
<td>Used in structural design of some buildings for fire conditions – usually not required for buildings in class “E”, which are the most popular industrial buildings</td>
</tr>
</tbody>
</table>
4 MAIN DESIGN FEATURES OF THE BUILDING

4.1 Fire load density

Typical approach used for the estimation of fire load density in Poland are inventory methods, such as old Polish standard PN-B 02852:2001 [6] or Eurocode 1-2 Annex E [10]. The designer has to know the materials stored in the volume, their packaging, mass and the area of the fire zone. Then, the fire load of each material is add up, and divided by the area – which gives the final fire load density (MJ/m²), that is used to derive most of fire safety requirements for a production/storage building. In case of Eurocode approach, the designer has additional benefits coming from reduction factors. It is uncommon in Poland to use performance engineering or more advanced fire load estimation methods (ie. NFPA 557 [11]).

\[
Q_d = \frac{\sum_{i=1}^{n} (H_{ci} \times G_i)}{F}
\]

where: 
- \(Q_d\) – fire load density [MJ/m²]
- \(Q_{ci}\) – heat of combustion of i- material [MJ/kg]
- \(G_i\) – mass of i-material [kg]
- \(F\) – area of the zone [m²]

The calculations of fire load density are presented in Table 2.

<table>
<thead>
<tr>
<th>Table 2. Fire Load Density calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenant 1</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Materials</td>
</tr>
<tr>
<td>Multiplier</td>
</tr>
<tr>
<td>Heat of combustion [MJ/kg]</td>
</tr>
<tr>
<td>Estimated mass</td>
</tr>
</tbody>
</table>
For mezzanine –
assumption of 500 MJ/m²
on area of 600 m²

Avg. mass of a palette –
250 kg
Total approx. mass of
1 944 t of stored goods

2) production
Assumption of 15 t of
goods in the production line

3) stored goods
144 shelves (9 palettes) –
total of 1 296 palettes,
avg. mass of palette – 250 kg -
324 t of stored goods

| Fire Load | 312 MJ/m² | 7 857 MJ/m² | 1 985 MJ/m² |
| Density   | Q < 500 MJ/m² | Q > 4000 MJ/m² | 1000 MJ/m² < Q < 2000 MJ/m² |

4.2 Sub-division into fire zones

The maximum areas allowed for the fire zones is dependent on the fire risk class of the building, which is determined by the designed fire load. The classes for a single level building are given in the table 3. If building is separated into fire zones from the foundation up to the top of the roof, each zone can be considered as separate building. Otherwise, the worst requirements apply. It is forbidden to make office building in the same fire zone as production, unless they are functionally connected. It is also forbidden to position a zone in higher class on zone with lower class, and the underground floor must be at least class “C”.

Table 3. Determination of the building fire risk class (single level building)

<table>
<thead>
<tr>
<th>Fire load density Q [MJ/m²]</th>
<th>Building class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q ≤ 500</td>
<td>„E”</td>
</tr>
<tr>
<td>500 &lt; Q ≤ 1.000</td>
<td>„D”</td>
</tr>
<tr>
<td>1.000 &lt; Q ≤ 2.000</td>
<td>„C”</td>
</tr>
<tr>
<td>2.000 &lt; Q ≤ 4.000</td>
<td>„B”</td>
</tr>
<tr>
<td>Q &gt; 4.000</td>
<td>„A”</td>
</tr>
</tbody>
</table>

Class E can be chosen for a single story building for storage/production, if all building elements are not spreading flame and there is a smoke and heat exhaust system if the building is > 1000 m²

Sprinkler system allows to choose class E for a single floor building, or for other buildings choose one class lower, than the table shows (E is the lowest class)

For the three tenants of hypothetical logistics building, the results of analysis till now are:

- Tenant 1, building class E (due to the office part in the mezzanine over loading deck, this class should also refer to the requirements for office buildings which is class D (§212.3), if sprinklers are used this can be lowered to E);
- Tenant 2, building class A, but since this kind of storage will almost always require use of sprinklers, this class can be lowered to E. If all construction elements are non-spreading the fire and there is SHEVS in the single story industrial building, the class can be also chosen as E, despite the lowering the class, the requirements for fire zone separation remain the same;
- Tenant 3, building class B, but similar to tenant 2 this class may be lowered to E under some circumstances.

Once the building class and the fire load density are known, the maximum area of the zone and requirements for building elements can be determined from the table 4.

Table 4. The maximum areas of fire zones in a single floor production/storage facility without a room with a risk of explosion

<table>
<thead>
<tr>
<th>Fire load</th>
<th>Maximum area of the fire zone (single floor building)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>basic</td>
</tr>
<tr>
<td>$Q &gt; 4.000$</td>
<td>2.000</td>
</tr>
<tr>
<td>$1.000 &lt; Q \leq 2.000$</td>
<td>8.000</td>
</tr>
<tr>
<td>$Q \leq 500$</td>
<td>20.000</td>
</tr>
</tbody>
</table>

If the building has more than one floor but is not higher than 25 m, half of above presented values apply, with the exception for $1.000 < Q \leq 2.000$ fire load class, for which the maximum zone area is $8000 / 12000 / 16000 / 20000$

An office cannot be a part of the fire zone of storage facility, unless it is functionally connected with that facility. This means, that:

a) if the office on the mezzanine above loading docks is a part of the storage fire zone, all requirements for the building must include the requirements for a so called “ZL III” class of human risk related to an office zone;

b) the mezzanine itself forms a separate fire zone, thus making the building two-story high – which automatically increases all the requirements for the structure of both fire zones. Fire resistance of structure underneath the office fire zone must be not lower than the fire resistance of the office zone itself.

Both proposed solutions can be considered “bad” for the investor, but it seems that more cost-effective solution is to leave the office on the mezzanine (although it has to be functionally connected with the storage!). In this case the length of evacuation route in this zone is much shorter, which creates a need to implement smoke and heat exhaust system in the fire zone, despite it is not required for this kind of building (and not needed in $<500$ MJ/m2 fire load class). In reality, such construction would not be included in the design, as it has too large economic consequence on the whole project – this office would be moved into a separate building or into a fire zone, but not above the docking bay.

From the maximum fire zone area calculations we obtain following maximum values:
- Tenant 1 – 20 000 m² is possible in this fire zone without any technical solutions, but due to fact that this zone has also an office, the requirements of maximum length of evacuation route apply as to office buildings, which will most likely require SHEVS for the required length of the evacuation route;
Tenant 2 – maximum area without sprinklers - 4 000 m², if sprinklers are used together with SHEVs and the building has only one floor, due to §230.2 the area of the zone is unlimited.

Tenant 3 – maximum area of 8 000 m² is possible in this fire zone without any technical solutions, due to type of occupancy and the risk management, it is advised to install sprinklers at least in the storage areas of the facility.

Solution 1 - office on mezzanine as part of industrial zone (only if connected functionally!)

Solution 2 - office separated into a separate fire zone, building is not a single story anymore!

Fig. 3. Two possible solutions for compartment of the office above the loading bay

Solution 1: Combination of SHEVS and sprinklers allows for unlimited fire zone area

Solution 2: Separate the fire zone into two separate zones

Fig. 4. Possible design choices for tenant 2
4.3 Structural requirements

Requirements for the structure of the building are chosen in accordance to fire risk class of the building, and are presented in tables 5 and 6. It must be noted, that the requirements for firestop partitions are as for original class of the building, despite the possibility to lower the class of the building into E. This means, that because of class “A” of tenant 2 space, the firestop partitions between the tenants will be REI 240. Please note that all of these requirements are referring to “R” class, which is related with standard temperature-time curve (sometimes exterior). This means, that despite proving that load-bearing of a structure within fire is maintained, these classes shall be obtained, unless it is allowed to omit them through a derogation from §216.

Table 5. Required fire resistance classes for the structure elements

<table>
<thead>
<tr>
<th>Building class</th>
<th>Main structure of the building</th>
<th>roof structure</th>
<th>roof</th>
<th>external walls (inter-storey band)</th>
<th>internal walls</th>
<th>roof covering</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;A&quot;</td>
<td>R 240</td>
<td>R 30</td>
<td>REI 120</td>
<td>EI 120(o-&gt;i)</td>
<td>EI 60</td>
<td>RE 30</td>
</tr>
<tr>
<td>&quot;C&quot;</td>
<td>R 60</td>
<td>R 15</td>
<td>REI 60</td>
<td>EI 30(o-&gt;i)</td>
<td>EI 15</td>
<td>RE 15</td>
</tr>
<tr>
<td>&quot;E&quot;</td>
<td>(−)</td>
<td>(−)</td>
<td>(−)</td>
<td>(−)</td>
<td>(−)</td>
<td>(−)</td>
</tr>
</tbody>
</table>

Table 6. Required fire resistance class for firestop partitions and elements

<table>
<thead>
<tr>
<th>Building class</th>
<th>Fire resistance of firestop partitions and elements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Firestop partitions</td>
</tr>
<tr>
<td></td>
<td>walls and ceilings in production/storage</td>
</tr>
<tr>
<td>„A“</td>
<td>R E I 240</td>
</tr>
<tr>
<td>„B“ and „C“</td>
<td>R E I 120</td>
</tr>
<tr>
<td>„D“ and „E“</td>
<td>R E I 60</td>
</tr>
</tbody>
</table>

If fire zones of the building are separated with a firestop partition, from the foundation to the roof, these fire zones can be treated as individual buildings. The firestop partition should rise above the top of the roof by 0,3 m. In the length of this wall, a strip with a class of fire resistance EI 60 has to be used, either 2 m wide on one side of the wall or 1 m on both sides of the wall (as shown on Figure 4).
4.4 Limiting the spread of fire

Polish technical regulations refer to old polish nomenclature on the flammability of materials, as shown in table 7 and 8. This has to be changed in a near future, as European Directive published in March 2016 does obligate Poland to use the Euroclass system.

Table 7. Nomenclature of reaction to fire, in relation to PN-EN 13501-1 (without floors)

<table>
<thead>
<tr>
<th>Polish classification / English translation</th>
<th>Określenie podstawowe</th>
<th>Określenie uzupełniające</th>
<th>Base class</th>
<th>Additional class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niepalny, Noncombustible</td>
<td>-</td>
<td>A1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Niezpalne, Fire-proof</td>
<td>A2</td>
<td>s1, s2, s3</td>
<td>d0</td>
<td></td>
</tr>
<tr>
<td>Trudno zapalne, Difficult to ignite</td>
<td>B</td>
<td>s1, s2, s3</td>
<td>d0, d1, d2</td>
<td></td>
</tr>
<tr>
<td>Łatwo zapalne, Easy to ignite</td>
<td>C</td>
<td>s1, s2, s3</td>
<td>d0, d1, d2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>s2, s3</td>
<td>d0, d1, d2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>-</td>
<td>-</td>
<td>d2</td>
</tr>
<tr>
<td></td>
<td>Niekapiące, non-drip</td>
<td>A2, B, C, D</td>
<td>s1, s2, s3</td>
<td>d0</td>
</tr>
<tr>
<td></td>
<td>Samogaszące, self-extinguishing</td>
<td>co najmniej E</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Intensywnie dymiące, intensive smoke production</td>
<td>A2, B, C, D</td>
<td>s3</td>
<td>d0, d1, d2</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>-</td>
<td>-</td>
<td>d2</td>
</tr>
</tbody>
</table>
Table 8. Nomenclature of reaction to fire, in relation to PN-EN 13501-1 (with floors)

<table>
<thead>
<tr>
<th>Polish classification / English translation</th>
<th>PN-EN 13501-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Określenie podstawowe</td>
<td>Base class</td>
</tr>
<tr>
<td>Określenie uzupełniające</td>
<td>Additional class</td>
</tr>
<tr>
<td>Floors</td>
<td>Smoke production</td>
</tr>
<tr>
<td>Niepalny Noncombustible</td>
<td>A1fl</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Trudno zapalne Difficult to ignite</td>
<td>Bfl, Cfl</td>
</tr>
<tr>
<td>Łatwo zapalne Easy to ignite</td>
<td>Dfl, Efl</td>
</tr>
<tr>
<td>Intensywnie dymiące intensive smoke production</td>
<td>A2fl, Bfl, Cfl, Dfl</td>
</tr>
<tr>
<td></td>
<td>Efl</td>
</tr>
</tbody>
</table>

Methods used for the estimation of reaction to fire are in accordance with standards:
- PN-EN 13823,
- PN-EN ISO11925-2,
- PN-EN ISO PN-EN ISO 1716
- PN-EN ISO 1182.

Additional classification relates the building elements into three classes of flame spread:
- **not spreading the fire**, which burn only in the proximity of flame, and the burning is not observed after commencement of tests, there are no burning droplets or falling burning parts of the element;
- **weakly spreading the fire**, which burn in area beside the proximity of flame, but within the scope of standards and classification, and there is no burning droplets or falling burning parts of the element;
- **strongly spreading the fire**, which burn beside the allowed area for weakly spreading the fire class, or burning droplets or falling burning parts of the elements are observed.

The relations between the spread of fire classes and Euroclass requirements are given in Appendix 3 to [1].

General rules that apply for hypothetical logistics building:
- inside office zones (ZL III) materials that are easy to ignite or which combustion products are highly toxic or have high soot yield should not be used;
- on evacuation routes easy to ignite materials shall not be used;
- in production/storage rooms, easy to ignite walls or partitions, interior finish elements and the floor material shall not be easy to ignite;
• ceilings and false ceilings are made with noncombustible or difficult to ignite materials, without burning droplets or elements
• thermal and acoustic insulation in HVAC installation and hot/cold water installation will be done in a way, that they do not spread the fire.

4.5 Separation distance

Just as the areas or the fire resistance class requirements, the separation distance is also dependent on the fire load and class of the building, and is shown in table 9.

Table 9. Separation distance matrix

<table>
<thead>
<tr>
<th>Distance between buildings of given classes</th>
<th>Human occupation (ie. office)</th>
<th>Livestock building</th>
<th>Production/storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q ≤ 1.000</td>
</tr>
<tr>
<td>Human occupation (ie. office)</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.000 &lt; Q ≤ 4.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q &gt; 4.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>Livestock building</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>15</td>
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<td>20</td>
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<tr>
<td>Production/storage Q ≤ 1.000</td>
<td>8</td>
<td>8</td>
<td>8</td>
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<td>20</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production/storage 1.000 &lt; Q ≤ 4.000</td>
<td>15</td>
<td>15</td>
<td>15</td>
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<tr>
<td></td>
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<td>15</td>
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<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production/storage Q &gt; 4.000</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

The area presented in the Table 7 is presenting just base values, that must be increased if glazing takes more than 35% of the wall area. Use of sprinklers allow to reduce the distance from table 7 by 25%.

If the building is near other building of the same type, and their combined area does not exceed the maximum size of fire zone (table 4), the separation distance can be omitted.

In many cases, there is need for derogation of separation distance requirement, as it may be difficult to meet it, when adjacent buildings are built at the edge of their lot. This may require additional performance engineering methods to prove, that risk for both buildings is not increased with this change – often in a form of radiation analysis – in a dedicated software such as Polish FireRad tool (fireplatform.eu) or as a part of CFD analysis. Some additional technical solutions, such as ie. water curtains, are sometimes used in such cases.
4.6 Evacuation requirements

A production building with size of 4 500 m² - 6 000 m² will require at least two separate exits. In production facilities, the maximum way that a person can travel to an exit out of the zone or into an evacuation route, from any point of the facility to this exit is 100 m. If the design does not show the usage of the facility, only 80% of this value is taken for the design calculations. The length of this way may be increased by:

- 25% if the height of the room is higher than 5 m (true for all tenants);
- 50% if sprinkler system is used;
- 50% if SHEVS is used.

These increments can be summed. The evacuation way may not lead through more than 3 compartments.

For tenant 1 the requirements can be different, as there is an office area functionally connected with the storage facility. In this case, the maximum length of evacuation way is 40 m (subject to the increments as above).

The evacuation way may end through an exit to an evacuation route – such as a corridor, stairwell etc., which walls have fire resistance as high as required for the internal walls (Table 5), but not less than EI 15. The length of all the corridors, stairwells etc. along the route, from the entrance to the exit to outside or different fire zone, is summarized, and in case of industrial facilities cannot exceed values presented in Table 10.
<table>
<thead>
<tr>
<th>Type of fire zone</th>
<th>Length of evacuation route</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>single direction</td>
</tr>
<tr>
<td>Industrial, Q &gt; 500 MJ/m²</td>
<td>30*</td>
</tr>
<tr>
<td>Industrial, Q &lt; 500 MJ/m²</td>
<td>60*</td>
</tr>
<tr>
<td>ZL III (offices)</td>
<td>30*</td>
</tr>
</tbody>
</table>

* not more than 20 m on a horizontal route

The lengths provided in Table 10 may be increased by:
- 50% if sprinkler system is used;
- 50% if SHEVS is used;
and this values can add up to 100%.

The physical dimensions of evacuation ways, routes or exits are dimensioned in connection with the amount of people in each fire zone. This calculations are done with factors of 5 m²/person in offices and 30 m²/person in industrial buildings. This means, that for fire zones of 6 000 m², the designer has to provide means of evacuation for 200 people. If the building design does unambiguously dictate the amount of fire zone users, it is required to use this value for the design.

There is no requirement for an given evacuation time from the building, other than requirements connected with the SHEVS performance based design.
4.7 Sprinkler system design

Sprinklers will be used in tenant 2 and 3 areas. The main “law” benefits from using sprinkler system, beside the fire protection provided by them, are:

- lower fire load density if following EC 1-2 method;
- lower building fire risk class (and in some cases class “E”);
- higher available area of the fire zone (in some cases unlimited);
- lower HRR for the design of SHEVS.

Choosing VdS CEA 4001 [12] standard as the base of the design, which is commonly used approach in Poland, the designer will receive following requirements for the sprinklers:

4.7.1 Tenant 1

*No sprinkler protection required for the expected occupation.*

4.7.2 Tenant 2

This tenant has to be protected with sprinklers underneath ceiling and additional intermediate sprinklers within the storage racks, as illustrated below on Figure 7.

- plastic commodities (PP/PE/PS) stacked for up to 8,00 m height, the stacking is in shelves, which height is limited to 2,00 m;
- class HHS IV;
- additional protection through intermediate levels of sprinklers, 3 levels of sprinklers at the shelves + sprinklers underneath the ceiling;
- ceiling sprinklers:
  - area of operation - 300 m²;
  - design density - 17,5 mm/min;

![Fig. 7. Protection of high storage (HHS III and IV), VdS CEA 4001 [12]](image-url)
- $K = 115$;
- amount of sprinklers $= \frac{6000}{9} \approx 670$;
- quick or normal response;
- **intermediate sprinklers:**
  - area of operation – 3 x 45 m$^2$;
  - design density – 10 mm/min;
  - $K = 80$;
  - 6 sprinklers per typical shelve with 2.7 m length;
  - quick response;
- design time – 90 min
- temperature index – 68°

If storage height is limited to 7.6 m, it is possible to use ESFR sprinklers with accordance to VdS CEA 4001, with following parameters:
- sprinkler type ESFR $K=200$;
- minimum P – 4.2 bar;
- design density – 45 mm/min;
- area of operation – 108 m$^2$;
- temperature index – 68°C.

If the designer choose different approach, ie. NFPA 13 [13], for storage height up to 9.1 m and building height of 12.00 m the requirements would be as follows:
- sprinkler type ESFR K16.8 ($K=240$);
- minimum P – 3.6 bar;
- area of operation – 108 m$^2$;
- temperature index – 68°C.

### 4.7.3 Tenant 3

**Storage of raw materials and ready products:**
- plastic commodities (wood, wooden products, foamed plastic) stacked for up to 3.80 m height,
- class HHS III;
- **ceiling sprinklers:**
  - area of operation - 26 m$^2$;
  - design density - 17.5 mm/min;
  - $K = 115$;
  - amount of sprinklers = $\frac{3000}{9} \approx 340$;
  - quick or normal response;
- **intermediate sprinklers:**
  - not required;
- design time – 90 min;
- temperature index – 68°.
Furniture production:
- wood, machinery, plastics – production process;
- class HHP I;
- ceiling sprinklers:
  - area of operation - 26 m²;
  - design density - 10 mm/min;
  - K - 115;
  - amount of sprinklers = 1500 / 9 - approx. 170;
  - quick or normal response;
- design time – 90 min;
- temperature index – 68°.

5  SMOKE AND HEAT VENTILATION SYSTEM DESIGN

5.1  Introduction

The performance requirements for Smoke and Heat Ventilation Systems are given in §270 of [1]:

“Smoke and heat ventilation system should (...) remove the smoke with efficiency that assures, that in time required to evacuate people on passages and evacuation roads there will not be smoke or temperature, that will make the safe evacuation impossible”

The legislature does not specify how the designer has to prove that his design does meet these criteria. Society of fire safety engineers and fire experts accepted that such evidence are either Computational Fluid Dynamics (CFD) numerical analysis of smoke and heat spread in the building, combined with computer evacuation model, or the direct fulfillment of Codes and Standards requirements for SHEVs. While group of producers and designers of mechanical Smoke and Heat Ventilation systems adjusted to this new reality by implementing CFD analysis as base requirement for a design, society interested in Natural Smoke and Heat Ventilation systems (NSHEVs) did not come up with unified design methodology for their systems. To date, the basis of many NSHEVs design is a standard, that is derived from the late 90s of last century [6]. Modern design guidelines such as NFPA 204 [7] are difficult to apply, resulting in many extra-curricular requirements, raising the cost of the investment. Moreover, broad use of CFD in NSHEVs design is much harder than in the case of mechanical ventilation, requiring an accurate numerical model of the analyzed building and its surroundings, with simultaneous evaluation of possible adverse weather conditions affecting the operation of the system.

For tenant 1, the system should provide means of escape not only from the ground level, but also from two levels of cat-walks. This may require not less than two different escape directions from the cat-walk, otherwise a person may be cut away by the fire plume alone. For tenant 2, the only level from which the evacuation is considered is ground level. If the zone is fit with ESFR sprinklers, the evacuation will not be aided by SHEVs, and the safe conditions should be sustained with solely the size of smoke reservoir. For tenant 3, designer has to consider three
different zones with different challenges. A fire in one zone should not endanger people or expensive equipment in other zones.

![Schematic of tenant 1 – required protection of cat-walks](image)

**5.2 Hand calculations**

**5.2.1 Polish Standard PN-B 02877-4:2001/Az:2006**

This is an old polish standard on the design for SHEVS systems in industrial buildings, having its roots in DIN 18232-2. The standard is outdated, but still used by some designers for industrial buildings, as in such applications the results obtained often can be considered “safe”. The calculation methodology in the standard requires an estimation of the risk of fire in the building by assigning materials stored therein to the corresponding groups from tables, and then matching it with required area of smoke ventilators. The area itself is presented as a percentage of horizontal projection of the surface area of a single smoke zone. This standard does not ensure compliance with the requirements cited earlier (§270 [1]), mainly due to the fact that system dimensioning is based on the size of compartment and not on the size of the likely fire, but it must be noted that for industrial applications, results obtained from this standard are very high. Additional problems with this methodology are:

- the lack of definition how to provide supply air to the system, beside requirement that total area of supply air openings should be 130% of total area of the smoke dampers, which is close to impossible to fulfill in very large buildings;
- the lack of definition of calculating the total surface of windows used as part of NSHEVs – standard does not distinguish horizontal and vertical ventilators;
- requirements that are impossible to meet – ie. the required distance of smoke damper in a stairwell from fireproof wall (which in most cases is the wall of the staircase) should not be less than 5 meters.

Following results were obtained with this methodology

**Tenant 1**

Height of smoke curtain – 3,075 m  
Height of smoke free layer – 8,925 m (0,75 H)
Maximum smoke zone area – 2 600 m²
Time of fire growth – 10 minutes (automatic alarm + normal conditions for Fire Service)
Fire growth speed – medium (Note: does not relate to a parameter!)
Packaging goods – M2 – Op1
Design group – 3
Aerodynamic area of ventilators, as the % of smoke zone area – 1.5%
Required aerodynamic area of ventilators in each of zones - 39 m²

Fig. 9. Sample separation of the fire zone into smoke zones

Fig. 10. Location of NSHEVs on the roof of building

Tenant 2 and 3

Height of smoke curtain – 6.00 m
Height of smoke free layer – 6.00 m (0.5 H)
Maximum smoke zone area – 2 600 m² (requires three zones!)
Time of fire growth – 10 minutes (automatic alarm + normal conditions for Fire Service)
Fire growth speed – very fast (Note: does not relate to a parameter!)
Packaging goods – M3/4 – Op2
Design group – 4
Aerodynamic area of ventilators, as the % of smoke zone area – 0.8%
Required aerodynamic area of ventilators in each of zones - 20,8 m²

This method in no way does account for the positive (extinguishing) effect of ESFR sprinklers.

Fig. 11. Division of the production zone (tenant3) into three smoke zones – required to protect the expensive industrial equipment from the fire of stored goods

Fig. 12. Location of NSHEVs on building roof

5.2.2 NFPA 204

A popular approach to the design of NSHEVs in Poland is to follow the requirements of NFPA 204. Large part in this has the Polish Chapter of SFPE, which published a translation of NFPA 204 into polish language. This approach is often applicable without further engineering analysis, and respected by AHJ as correct.

Tenant 1
For an archive, the expected growth of fire is slow. With an estimation of Fire Brigade arrival, and the start of firefighting operation of 15 - 20 minutes, without any sprinklers, the fire may reach:

\[ Q = 1200^2 \times 0.00293 \text{ kW/s}^2 = 4219 \text{ kW} \]

This estimation is realistic – in archives with metal racks (with full side walls), the growth of fire is heavily limited with the physical compartmentation between the flammable materials. Other assumptions are:

- Maximum distance between smoke curtains – \( 8 \times H = 8 \times 12 = 96 \text{ m} \) (whole zone)
- Height of smoke free layer – 9.8 m.

The compartmentation distance between storage racks, can be calculated with formula from NFPA 204, that relates the distance to the root of HRR, for an ignition flux value 20 kW/m². For HRR = 4219 kW, this distance is 2.73 m. In a complex system of walls and floors (ie. mezzanines, cat-walks etc.), estimation of this distance may be done with advanced dedicated software (ie. FireRad, fireplatform.eu), or as a part of CFD study, as shown on figure 13.

---

**Fig. 13.** Radiative flux between the storage zones for 5 MW and 10 MW fires
Required total aerodynamic free area of all smoke ventilators – 39.6 m². This area should allow for keeping the smoke above the smoke free layer – a verification for the AHJ may be required, but usually the calculations itself should be good enough proof of system performance.
Tenant 2

The growth of fire, of high storage of plastic commodities may be considered as ultra-fast $\alpha t^2$. In accordance with VDI6019-1, the ESFR sprinklers at height of 10 m can activate after 155 seconds, for height of 12 m this can be interpolated into approx. 180 seconds. With additional 60 seconds of safety margin, this leads into growth of fire in 240 seconds, that relates to 10 805 kW HRR of the fire. It is expected that the SHEVS will not operate automatically, and that the ESFR sprinklers will gain control over fire immediately, and lead into extinguishing of the fire.

In this case the design of SHEVS is not the critical aspect of the fire safety, and so some simplifications can be done (ie. lowering the height of smoke reservoir to 0,5 H).
For this case, it is possible to remove the smoke sufficiently with less than 10 m² of aerodynamic free area of ventilators. The AHJ should allow this without further verification, but it might be require to prove, that there is no adverse interaction between the SHEVs and ESFR sprinklers, and that with non-working SHEVS the safe evacuation conditions are provided.

**Tenant 3**

In this case, it might be required to separate the area into three smoke zones, due to need to protect the industrial equipment in the middle zone (the production area). The height of smoke curtains can be ~0.5 H, as this will be sufficient for the operation of the facility, and in the same time allow for more efficient system design.

The fire of stacks of wooden products can be considered as fast $\alpha t^2$. In accordance with VDI 6019-1 the normal activation time sprinklers will activate after approx. 355 s. With additional 60 seconds of safety margin, this leads to fire growing for 415 s, that relates to 8 077 kW. It is expected that sprinklers obtain control over the growth of fire.

\[
\begin{align*}
Q_C &= 0,7 \cdot Q = 5633,9 \\
D &= \left[ \frac{4 \cdot Q}{\alpha \cdot Q_{totsqm}} \right]^{\frac{1}{2}} = 3,2069 \\
L &= 1,02 \cdot D = 0,239 \cdot Q^{\frac{2}{5}} = 5,3185 \\
\varpi &= \left[ \frac{2 \cdot \alpha \cdot Q}{(J \cdot x)^2} \right]^{\frac{1}{2}} x_\varpi = 0,083 \cdot Q^{\frac{3}{5}} - 1,02 \cdot D = 0,2973 \\
\varpi_p &= 0,071 \cdot Q_C \left[ \frac{2}{3} \right] \left[ 1 - 0,027 \cdot Q_C \left( \frac{z}{L} \right)^{\frac{2}{3}} \right] \left( \frac{z}{L} \right)^{\frac{2}{3}} = 37,9705
\end{align*}
\]

Fig. 18.  Hand calculations of required area of ventilators (comparison of mass of smoke in plume and removed from the building)

Fig. 19.  Location of NSHEVs on the building roof
For this case, it is possible to remove the smoke sufficiently with less than 10 m² of aerodynamic free area, but it is required to separate the building into three smoke zones. The AHJ should allow this without further verification.

5.3 Numerical analysis

Numerical studies were performed in ANSYS Fluent software (v14.5). In all of the scenarios the fire was modelled as volumetric heat and smoke source, with maximum HRR shown in table below. The growth of fire was linear – steady state results were investigated. When time to reach a certain parameter was estimated, the fire was modelled as $\alpha t^2$, with the value of $\alpha$ coefficient dependant on the tenant. It was assumed that the smoke was produced in combustion of materials with average heat of combustion 20,00 MJ/kg. Smoke was modelled as a perfect gas with all physical properties as air, beside the specific heat which was constant at 1,00 kJ/kg.

Following physical sub-models were used for the calculations:
- turbulence model - RNG $k$-$\varepsilon$,
- fire model - transient volumetric source of heat and smoke, without combustion
- radiation model - P1,
- heat transfer model, third type boundary condition.

The modelling was transient, and the assessment of SHEVs performance was done 5 minutes after the maximum HRR was reached, with the assumption the conditions are close to a steady state.
### Simulation scenarios

#### Table 11. CFD scenario matrix

<table>
<thead>
<tr>
<th>ID</th>
<th>Area</th>
<th>Goal</th>
<th>Max. HRR</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Tenant 1</td>
<td>Verification of PN-B system (6.1)</td>
<td>5 MW</td>
<td></td>
</tr>
<tr>
<td>02</td>
<td>Tenant 1</td>
<td>Verification of PN-B system (6.1)</td>
<td>10 MW</td>
<td></td>
</tr>
<tr>
<td>03</td>
<td>Tenant 1</td>
<td>Verification of NFPA 204 (6.1)</td>
<td>5 MW</td>
<td></td>
</tr>
<tr>
<td>04</td>
<td>Tenant 1</td>
<td>Verification of NFPA 204 (6.1)</td>
<td>10 MW</td>
<td></td>
</tr>
<tr>
<td>05</td>
<td>Tenant 1</td>
<td>Optimization approach #1</td>
<td>5 MW</td>
<td></td>
</tr>
<tr>
<td>06</td>
<td>Tenant 1</td>
<td>Optimization approach #1</td>
<td>10 MW</td>
<td></td>
</tr>
</tbody>
</table>
| 07  | Tenant 1   | Wind coefficient analysis, medium wind speed | u_{ref} = 4.67 m/s | Wind attack angle: a) 0°  
                      | a-g | Tenant 1 | Wind coefficient analysis, medium wind speed | u_{ref} = 4.67 m/s | Wind attack angle: a) 0°  
                      | b-g | Tenant 1 | Wind coefficient analysis, high wind speed  | u_{ref} = 10 m/s  | Wind attack angle: a) 0°  
                      | 08  | Tenant 1   | Optimization approach #2, fire performance under wind influence, u_{ref} = 1 m/s, \( \alpha = 135^\circ \) | 5 MW     |                                           |
| 09  | Tenant 1   | Optimization approach #2, fire performance under wind influence, u_{ref} = 1 m/s, \( \alpha = 135^\circ \) | 10 MW    |                                           |
| 10  | Tenant 1   | Optimization approach #2, fire performance under wind influence, u_{ref} = 4.67 m/s, \( \alpha = 135^\circ \) | 5 MW     |                                           |
| 11  | Tenant 1   | Optimization approach #2, fire performance under wind influence, u_{ref} = 4.67 m/s, \( \alpha = 135^\circ \) | 10 MW    |                                           |
| 12  | Tenant 1   | Optimization approach #2, fire performance under wind influence, u_{ref} = 4.67 m/s, \( \alpha = 135^\circ \) | 15 MW    |                                           |
| 13  | Tenant 1   | Optimization approach #2, fire performance under wind influence, u_{ref} = 4.67 m/s, \( \alpha = 135^\circ \) | 5 MW     |                                           |
| 14  | Tenant 1   | Optimization approach #2, fire performance under wind influence, u_{ref} = 4.67 m/s, \( \alpha = 135^\circ \) | 10 MW    |                                           |
| 15  | Tenant 1   | Optimization approach #2, fire performance under wind influence, u_{ref} = 4.67 m/s, \( \alpha = 135^\circ \) | 15 MW    |                                           |
| 16  | Tenant 1   | Optimization approach #2, fire performance under wind influence, u_{ref} = 10 m/s, \( \alpha = 135^\circ \) | 5 MW     |                                           |
| 17  | Tenant 1   | Optimization approach #2, fire performance under wind influence, u_{ref} = 10 m/s, \( \alpha = 135^\circ \) | 10 MW    |                                           |
| 18  | Tenant 2   | Estimation of temperature field for ESFR protected area | 10,8 MW  |                                           |

For the scenarios including the wind, it was described with use of logarithmic profile, with reference velocity of \( u_{ref} \) at height of 10 m, for terrain roughness 0,30 m.

### Numerical model

Three separate numerical models were created, that differ in the size of the numerical domain. Models are shown on Figure 20. These three models represent three different approaches to numerical modelling:

a) model simplified to include only the interior of the building, outlets modelled as pressure boundary conditions;

b) model simplified to include the interior of the building, and nearest exterior, outlets modelled as opening in the walls along with their most important features, pressure boundaries at the edges of the domain;

c) model suitable for wind engineering, with exterior domain large enough to not influence the flow around the building, outlets modelled in details as physical openings with all of their features, pressure boundaries at the edges of the domain with velocity boundary including logarithmic wind profile on XZ plane.
The first approach (a) is sufficient only for most basic, preliminary analysis. The simplification in modelling the inlets and outlets will strongly influence the performance of NSHEVs. This approach is valid when modelling flows with no ventilation operation, such as investigation of temperature field within the domain, for ESFR sprinkler actuation. The second approach (b) is valid for NSHEV performance analysis, but without any wind interaction. This approach can be used for checking the environmental conditions connected to the evacuation process inside the building, but the designer must add a margin of safety to the results, as in wind conditions they may be significantly worse. The third approach (c) is used for precise evaluation of NSHEVs performance in wind conditions, for different wind angles, also in combination with optimizing additional exterior features of the building.
5.4 Verification of the designed solutions

For tenant 1, two different design approaches were considered:

- PN-B 02877-4:2001/Az:2006, separation of the volume into two smoke zones and approx. 39.6 m² of aerodynamic area of exhaust points, air inlets not less than 130% of area of exhaust; verified in scenarios 01 and 02;
- NFPA 204, whole area is a part of single smoke zone, aerodynamic free area of ventilators of 39.6 m², expected size of the fire less than 5 MW; verified in scenarios 03 and 04.

Proposed solutions were further optimized in simulations 05 and 06, in which after first approach to optimization, the aerodynamic free area of smoke ventilators in the single smoke zone was limited to approx. 30 m².

Numerical model used in every simulation was modified slightly, to fit the ventilation concept being investigated. For this approach, numerical model (b) described in chapter 5.3 was employed. In every analysis, the air supply was provided by loading bay doors that formed one of the building walls, underneath the office mezzanine. It was assumed, that the mezzanine is either separated through walls or a smoke curtain, as explained in chapter 4.2.

Fire was modelled as a volumetric source of heat and smoke, with total volume of 16 m³, which translates into HRR_PUA value of 312.5 kW/m³ for 5 MW fire and 625 kW/m³ for 10 MW fire. Soot yield value in every simulation was Ys = 0.07 g/g and Hc_eff = 20 MJ/kg.

5.4.1 PN-B 02877-4:2001/Az:2006

For both fire size (5 MW and 10 MW) the system was efficient, and kept the smoke at the designed height (~9 m above the floor). The temperature in the upper layer was greatly limited, exceeding 200°C only in the plume area. This means, that the heat returned back into the archive was limited. Both evacuation and rescue operations were possible in the whole length of the simulation. Small amount of smoke did cross into neighbouring smoke zone.
Fig. 23. Temperature distribution (20°C – 200°C and more) after simulation reached a steady state, 5 MW fire, scenario 01

Fig. 24. Temperature distribution (20°C – 200°C and more) after simulation reached a steady state, 5 MW fire, scenario 02

Fig. 25. Mass density of smoke (0,00 – 0,20 g/m³ and more) after simulation reached a steady state, 5 MW fire, scenario 01
5.4.2 NFPA 204

For both fire sizes (5 MW and 10 MW) the system was efficient, and kept the smoke above height of evacuation routes in the whole duration of the simulation. From the protection of goods point of view, the upper shelves of the archive were inside the smoke reservoir, as for the 5 MW fire the layer positioned at height of approx. 7,00 m and for 10 MW at approx. 6,40 m. Beside the plume region, the temperature of the smoke was not exceeding 60°C, so the thermal damage to the commodities would be low, although the adverse effects of contact with smoke will be observed.
Fig. 28. Temperature distribution (20°C – 200°C and more) after simulation reached a steady state, 10 MW fire, scenario 04

Fig. 29. Mass density of smoke (0.00 – 0.20 g/m³ and more) after simulation reached a steady state, 5 MW fire, scenario 03

Fig. 30. Mass density of smoke (0.00 – 0.20 g/m³ and more) after simulation reached a steady state, 10 MW fire, scenario 04
5.4.3 Optimization approach #1

Since NFPA approach did not provide protection of stored commodities from smoke (the layer was at height of ~6 – 7 m), but provided sufficient evacuation and rescue operation conditions, it may be possible to optimize the solution further for just this key aspect of safety. Another instance of system designed, employing approx. 30 m² of aerodynamic free area of ventilators.

System provided similar performance as the earlier iterations, with the exception of smoke free layer height, that felt down to 5 – 6 meters (and varied in the length of the archive). Both evacuation and rescue operations were possible within the building. Average temperature of smoke within the reservoir did not exceed 60°C, at height of the top layer of the archive.

![Fig. 31. Temperature distribution (20°C – 200°C and more) after simulation reached a steady state, 5 MW fire, scenario 05](image1)

![Fig. 32. Temperature distribution (20°C – 200°C and more) after simulation reached a steady state, 10 MW fire, scenario 06](image2)
5.5 Optimization study under wind conditions

With optimization approach #1, the system was modified, so it does include smallest amount of ventilators, that should theoretically allow safe evacuation and rescue operation conditions within the building. The designer must know though, that the CFD performed without any wind influence, can often lead to an overestimation of system performance, that may be much lower, once the wind is included in the analysis. As a reference – if one compares Cvv value of a natural ventilator to its Cv0 value (with and without wind), it may be easily noted, that without wind the performance of ventilator is from 10% to 20% higher.

Including the wind together with a fire analysis is a tedious task. It is impossible to guess, which wind direction will be the worst condition for the fire, as local structures or geographical features of the terrain may strongly influence this. On other hand, investigating multiple wind attack angles together with a fire simulation is extremely time and resource consuming task. To make this task as simple as possible, the analysis may be separated into two steps.
The first step, wind analysis, is a method to evaluate the wind influence over external features of the building, without a fire (and often without interior model). This analysis relies on statistical wind data for the area, in which the building is located. Numerical model used in the study should consist not only of the building analysed, but also its surroundings that may have an effect on the flow around it. The model has to be built in a way, that allows free rotation in order to evaluate multiple wind angles. The analysis itself is steady-state, and averaged conditions are estimated (thus the use of k-ε turbulence modelling over LES model that is better for peak value assessment). Analysis of the results of such study often comes down to evaluation of wind coefficient in areas on which elements of natural smoke exhaust system are located.

Worst case scenario is usually the case with highest pressure on area with ventilators, highest underpressure in areas where inlet air openings are located or the case in which highest air velocity inside the building is observed. It is possible, that this analysis will yield multiple scenarios to be evaluated in further CFD studies. Although relatively simple, this analysis may be quite difficult, mainly because of need for simultaneous simulation of effects of both large-scale buildings and other environmental obstacles and small scale elements of natural smoke and heat exhaust system and other elements that may affect the aerodynamics of the roof. Once the worst case scenario (or scenarios) are determined, step two of the analysis is performed, which is a transient simulation with a fire within the building in the worst wind conditions.

Fig. 35. Numerical model used in the wind influence analysis
Fig. 36. Wind pressure coefficient, angle of attack 0°, for \( u_{ref} = 4.67 \text{ m/s} \) and 10 m/s

Fig. 37. Wind pressure coefficient, angle of attack 15°, for \( u_{ref} = 4.67 \text{ m/s} \) and 10 m/s

Fig. 38. Wind pressure coefficient, angle of attack 45°, for \( u_{ref} = 4.67 \text{ m/s} \) and 10 m/s

Fig. 39. Wind pressure coefficient, angle of attack 90°, for \( u_{ref} = 4.67 \text{ m/s} \) and 10 m/s
Fig. 40. Wind pressure coefficient, angle of attack 120°, for uref = 4.67 m/s and 10 m/s

Fig. 41. Wind pressure coefficient, angle of attack 135°, for uref = 4.67 m/s and 10 m/s

Fig. 42. Wind pressure coefficient, angle of attack 180°, for uref = 4.67 m/s and 10 m/s

Fig. 43. Sample of practical use of this method in a real building application (authors archive)
Second step of the analysis is the analysis of the natural smoke and heat exhaust system performance in the case of fire. Typical parameters that are investigated are: temperature and local visibility at evacuation routes, temperature of the smoke removed by the system and the mass of air removed through the ventilators.

In the case of hypothetical logistics centre - Tenant 1, that smallest area of ventilators that is sufficient to provide required conditions for evacuation and rescue operations, is approx. 27 m². With this area, it was possible to remove the smoke from the reservoir, although for wind speed close to 10 m/s, some mixing with air is observed and lower part of the building is filling slowly with low density smoke.

Negative influence of wind is observed, especially in terms of non-uniform height of smoke layer throughout the building, and mixing between air and smoke in the lower layer. Overall performance of the system may be compared with the performance of NFPA 204 design.
Fig. 46. Mass density of smoke ($0.00 - 0.20 \text{ g/m}^3$ and higher) in a plot through the building, 5 MW fire, steady state conditions, $u_{ref} = 1 \text{ m/s}$

Fig. 47. Temperature ($20^\circ\text{C} - 200^\circ\text{C}$ and higher) in a plot through the building, 10 MW fire, steady state conditions, $u_{ref} = 1 \text{ m/s}$

Fig. 48. Mass density of smoke ($0.00 - 0.20 \text{ g/m}^3$ and higher) in a plot through the building, 10 MW fire, steady state conditions, $u_{ref} = 1 \text{ m/s}$
Fig. 49. Temperature (20°C – 200°C and higher) in a plot through the building, 15 MW fire, steady state conditions, $\text{uref} = 1 \text{ m/s}$

Fig. 50. Mass density of smoke (0,00 – 0,20 g/m³ and higher) in a plot through the building, 15 MW fire, steady state conditions, $\text{uref} = 1 \text{ m/s}$

Fig. 51. Temperature (20°C – 200°C and higher) in a plot through the building, 5 MW fire, steady state conditions, $\text{uref} = 4,67 \text{ m/s}$
Fig. 52. Mass density of smoke (0.00 – 0.20 g/m³ and higher) in a plot through the building, 5 MW fire, steady state conditions, $u_{ref} = 4.67$ m/s

Fig. 53. Temperature (20°C – 200°C and higher) in a plot through the building, 10 MW fire, steady state conditions, $u_{ref} = 4.67$ m/s

Fig. 54. Mass density of smoke (0.00 – 0.20 g/m³ and higher) in a plot through the building, 10 MW fire, steady state conditions, $u_{ref} = 4.67$ m/s
Fig. 55. Temperature (20°C – 200°C and higher) in a plot through the building, 15 MW fire, steady state conditions, \( u_{ref} = 4.67 \, \text{m/s} \)

Fig. 56. Mass density of smoke \((0.00 – 0.20 \, \text{g/m}^3 \text{ and higher})\) in a plot through the building, 15 MW fire, steady state conditions, \( u_{ref} = 4.67 \, \text{m/s} \)

Fig. 57. Temperature (20°C – 200°C and higher) in a plot through the building, 5 MW fire, steady state conditions, \( u_{ref} = 10 \, \text{m/s} \)
Fig. 58. Mass density of smoke (0.00 – 0.20 g/m³ and higher) in a plot through the building, 5 MW fire, steady state conditions, $u_{ref} = 10$ m/s

Fig. 59. Temperature (20°C – 200°C and higher) in a plot through the building, 10 MW fire, steady state conditions, $u_{ref} = 10$ m/s

Fig. 60. Mass density of smoke (0.00 – 0.20 g/m³ and higher) in a plot through the building, 10 MW fire, steady state conditions, $u_{ref} = 10$ m/s
Fig. 61. Temperature (20°C – 200°C and higher) in a plot through the building, 15 MW fire, steady state conditions, $u_{ref} = 10$ m/s

Fig. 62. Mass density of smoke (0.00 – 0.20 g/m³ and higher) in a plot through the building, 15 MW fire, steady state conditions, $u_{ref} = 10$ m/s
6 INSTALLATION OF NSHEVS IN ESFR PROTECTED SPACE

If the designer decides that ESFR sprinklers are better solution than additional intermediate layers of sprinklers, as shown in chapter 4.7, there is a problem with coexistence of SHEV system and the ESFR sprinkler system. Due to their unique ability to extinguish fire, ESFR sprinklers are especially fragile to any change in the temperature field in their proximity. ESFR operation relies on the fact, that Actual Delivered Density (ADD) parameter is higher than Required Delivered Density (RDD) at the moment of sprinkler actuation. With ultra-fast type of fires, delay of sprinkler activation of even one minute may lead to catastrophic consequences, as the installation may never be able to catch up with the raging fire. On other hand the Smoke and Heat Exhaust Ventilation systems work by removing heat from the upper layer – limiting the temperature in the smoke reservoir, but barely affecting the growth of fire. It is obvious, that such installation should not operate, until ESFR sprinklers are active. Problems arise with the Polish law system, which for many benefits connected to smoke venting (see chapter 4), require an automatic SHEV system. To make a system, which could be started only by only a manual mean, it would be required to obtain a derogation, which is a time and resource consuming effort.

The coexistence of ESFR sprinklers is barely regulated within standard framework. NFPA based documents point, that such installations should not be used together, or that ventilators should be equipped with 182°C actuators. VdS 2815:2013-09 allows only manual mode for NSHEVs in ESFR sprinkler protected facilities.

The best solution in this case is to design actuators for NSHEVs with operating temperature of 140°C or 182°C, that allow sprinklers operate long before the SHEVS. At the same time, if for some case the sprinklers do not actuate, the SHEVS will provide a minimum protection for the buildings structure. If SHEVS are operated by smoke detection system, a minimum 5 minute delay shall be applied for their actuation, or a logical connection between sprinkler valve and FAS system shall be made.

If such solutions are employed in the building, it might be valuable to present to AHJ, that despite the delay in system operation, by only the volume of smoke reservoir, safe conditions for human evacuation and safety operations are met. Sample of such analysis are shown below. Numerical model (a) is used for this, as this analysis does not include removal of smoke from the building through natural means. The temperature measured within the simulation quickly reaches more than 100°C directly above the plume region, and after 3 minutes this temperature is measured underneath a ceiling on more than 18 m² (double area of sprinkler operation). After the margin of safety time included (60 s), the temperature exceeds 200° in the plume region, and is high above 100°C in a large part of the ceiling area. This shows, how rapid is the growth of fire and the release of vast amount of heat. Once 240 s is reached, the HRR modelled falls down, to be completely extinguished in 600 s of the analysis. In that moment, it is still possible to enter the building and locate the fire, although some smoke may be noticed in the lower layer.
Fig. 63. Temperature (20°C – 200°C and more) plot through the building in 120 s of the analysis (HRR = 2701 kW)

Fig. 64. Temperature (20°C – 200°C and more) plot through the building in 180 s of the analysis (HRR = 6078 kW)

Fig. 65. Temperature (20°C – 200°C and more) plot through the building in 240 s of the analysis (HRR = 10 085 kW)
Fig. 66. Temperature (20°C – 200°C and more) at the height of 11.50 m, 120 s of the analysis (HRR = 2701 kW)

Fig. 67. Temperature (20°C – 200°C and more) at the height of 11.50 m, 180 s of the analysis (HRR = 6078 kW)

Fig. 68. Temperature (20°C – 200°C and more) at the height of 11.50 m, 240 s of the analysis (HRR = 10085 kW)
Fig. 69. Temperature (20°C – 200°C and more) in a plot through the building, in the moment of manual actuation of NSHEV (10 minutes after the ignition)

Fig. 70. Mass density of smoke (0.00 – 0.20 g/m³ and more) in a plot through the building, in the moment of manual actuation of NSHEV (10 minutes after the ignition)
7 REFERENCES

[1] Dz.U. 2002 nr 75 poz. 690 Rozporządzenie Ministra Infrastruktury z dnia 12 kwietnia 2002 r. w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie, wraz z późniejszymi zmianami;

[2] Rozporządzenie Ministra Spraw Wewnętrznych i Administracji z dnia 7 czerwca 2010 r. w sprawie ochrony przeciwpożarowej budynków, innych obiektów budowlanych i terenów (Dz. U. nr 109, poz. 719), z późniejszymi zmianami

[3] Ustawa z dnia 7 lipca 1994 r. - Prawo budowlane


