INLUENCE OF FIRE PROTECTION METHODS ON SUSTAINABILITY OF BUILDINGS

Author: Poonam Moodambail

Supervisor: Prof. František Wald

University: Czech Technical University in Prague

European Commission
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Faculty of Civil Engineering
Thákurova 7, 166 29 Prague 6, Czech Republic

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Sensitivity study of major structural parameters
Comclusion

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Poonam Moodambail

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Lastly, I would like to dedicate this thesis to my family, who have showered me with their endless love, support and encouragement. They are the reason for who I am today and I look forward to fulfilling their wishes to the best of my ability.

Abstract

Designing for fire is an important aspect in the design process of buildings and civil engineering structures. In Europe the requirements for fire design are specified in the national annexes and all buildings are required to comply with the conditions. This requirement is linked to the required survival time of the structure in standard fire tests. Most commonly the structure is designed for ambient temperature and the fire requirement is mostly satisfied by use of external fire protection in order to keep the temperature of the members below the critical value.

With increasing awareness of the huge environmental effect that the construction industry has in the industrial sector, it is now becoming a practice to focus on sustainability in design and construction of buildings. But when it comes to fire design, the emphasis on the sustainability of these methods gets a lower priority than the fire design as the effects of a fire catastrophe can be disastrous. Many active and passive methods of fire protection systems are being developed as a result of recent fire disasters and also the industry is focusing on developing the life cycle assessment of these individual products or systems in the form of Environmental Product Declarations (EPD). This dissertation is an attempt to combine these two important aspects of the building industry and understand the influence of the fire protection methods on the sustainability and compare the different fire protection systems in this regard. With the use of software for sustainability calculations for buildings and use of EPDs for individual materials, the life cycle assessment for a complete building model has been performed and the results have been analysed.

Key words

Life cycle assessment, fire design

Table of Contents

DECLARATION 1
ACKNOWLEDGEMENTS 2
ABSTRACT 3
1. STATE OF ART 6
1.1. Introduction 6
1.2. Fire Design of Steel structures 6
1.2.1. Mechanical Loading 6
1.2.2. Thermal Action 8
1.2.3. Temperature in Members 9
1.2.4. Mechanical Analysis 13
1.2.5. Fire resistance of Steel Members 18
1.2.6. Fire resistance of Composite Member 19
1.2.7. Methods of Fire Protection 20
1.2.8. Software – Elefir EN 22
1.3. Sustainability 25
1.3.1. Introduction 25
1.3.2. Methodologies for Building sustainability assessment 26
1.3.3. Framework for Life Cycle Assessment 26
1.3.4. Building level (EN 15978, 2011) 27
1.3.5. Product Level (EN 15804, 2012) 33
1.3.6. AMECO 33
2. OBJECTIVES 35
3. CASE STUDY 36
3.1. Building model 36
3.2. Fire Resistance Check 38
3.3. Fire protection 41
4. SENSITIVITY STUDY 49
4.1. AMECO - Input 50
4.2. Fire protection 52
4.3. Environmental Impact 53
4.3.1. Best Case: Case 9 54

4.3.2. Worst Case – Case 6 56
4.3.3. Comparison between the Best and Worst solutions 58
4.4. Resource Use 59
4.4.1. Best Case –Case 9 60
4.4.2. Worst Case 62
4.4.3. Comparison between the Best and Worst solutions 63
4.5. Waste categories 64
4.5.1. Best Case 65
4.5.2. Worst Case 66
4.5.3. Comparison between the Best and Worst solutions 67
5. OBSERVATIONS AND SUMMARY 69
6. FUTURE STUDY 71
7. REFERENCES 72
8. ANNEX 74
8.1. Environmental Impact 74
8.2. Resource Use 79
8.3. Waste Categories 84

1. State of Art

2.1. Introduction

The following chapter will describe in detail the concepts used for the fire design and the sustainability calculations of the building model. An effort has been made to understand the interaction between the 2 fields. The basics of both fields have been covered since the design for fire has also been performed on the building model

2.2. Fire Design of Steel structures

The design for fire must be performed in such a way that in case of outbreak of fire

- The load bearing capacity of the construction can be assumed for a specific period of time
- The generation and spread of fire and smoke within the structure is limited
- Spread of fire to neighbouring constructions is avoided.
- Occupants can safely vacate or be rescued by other means
- Safety of rescue teams is considered.

Eurocodes for fire design

Eurocode	At room temperature	In case of fire
0 : Basis of design	EN 1990	-
1 : Actions EN 1991-1-1	EN 1991-1-1	EN 1991-1-2
2 : Concrete structures	EN 1992-1-1	EN 1992-1-2
3 : Steel structures	EN 1993-1-1	EN 1993-1-2
4 : Composite steel-concrete structures	EN 1994-1-1	EN 1994-1-2
5 : Timber structures	EN 1995-1-1	EN 1995-1-2
6 : Masonry structures	EN 1996-1-1	EN 1996-1-2
7 : Geotechnical design	EN 1997	
8 : Earthquake resistance	EN 1998	
9 : Aluminium alloy structures	EN 1999-1-1	EN 1991-1-2

2.2.1. Mechanical Loading

The fire situation is classified as an accidental situation in the Eurocode EN 1990:2002. The design effect for the fire loading combination can be obtained using the combination of actions for accidental situation given by equations

$$\sum_{j\geq\sim1} G_{k,j} + P + A_d + \psi_{1,1} Q_{k,1} + \sum_{i\geq2} \psi_{2,i} Q_{k,i}$$

or

$$\sum_{j\geq\sim1} G_{k,j} + P + A_d + \sum_{i\geq1} \psi_{2,i} Q_{k,i}$$

All the permanent actions are taken as their characteristic values. The values of imposed load are significantly lower in the fire situation than at ambient temperature. Due to this even lower permanent loads have a higher importance during fire. The term A_d represents the indirect fire actions. In the following study indirect actions will not be taken into consideration.

The difference between the 2 equations lies in the coefficient Ψ Applied to the leading variable action. The coefficient for the frequent value Ψ_1 is considered in the first equation whereas the coefficient for the quasi permanent action Ψ_2 is considered in the second. (Franssen, J-M:2010). The recommended values are given in the table below.

Recommended values of Ψ factors for buildings (EN 1990:2002)

Action	ψ_0	ψ_1	ψ_2
Imposed loads in buildings, category (see EN 1991-1-1)			
Category A : domestic, residential areas	0,7	0,5	0,3
Category B : office areas	0,7	0,5	0,3
Category C : congregation areas	0,7	0,7	0,6
Category D : shopping areas	0,7	0,7	0,6
Category E : storage areas	1,0	0,9	0,8
Category F : traffic area, vehicle weight ≤ 30kN	0,7	0,7	0,6
Category G : traffic area, 30kN < vehicle weight ≤ 160kN	0,7	0,5	0,3
Category H : roofs	0	0	0
Snow loads on buildings (see EN 1991-1-3)*			
Finland, Iceland, Norway, Sweden	0,70	0,50	0,20
Remainder of CEN Member States, for sites located at altitude H > 1000 m a.s.l.	0,70	0,50	0,20
Remainder of CEN Member States, for sites located at altitude H ≤ 1000 m a.s.l.	0,50	0,20	0
Wind loads on buildings (see EN 1991-1-4)	0,6	0,2	0
Temperature (non-fire) in buildings (see EN 1991-1-5)	0,6	0,5	0
NOTE The ψ values may be set by the National annex. * For countries not mentioned below, see relevant local conditions.			

Often the structures are designed at ambient temperatures before considering the fire situation. In some cases it may be easier to use simplified methods to calculate the loading in fire condition. Eurocode 1(EN 1991-1-2:2005) suggests that the effect of actions in the fire situation $E_{fi,d}$ may be obtained from the multiplication of the effect of actions at ambient temperature E_d by a scalar reduction factor n_{fi}.

$$E_{fi,d,t} = \eta_{fi} E_d$$

From Eurocode 3, the reduction factor can be determined as

$$\eta_{fi} = \frac{G_k + \psi_{fi} Q_{k,1}}{\gamma_G G_k + \gamma_{Q,1} Q_{k,1}}$$

If n_{fi} is given as a reference load level, this load level is the ratio between the actions in the fire situation and resistance of the member at room temperature.

$$\eta_{fi} = \frac{E_{fi,d}}{R_d}$$

This equation can be used in the verification process when the member is known.

2.2.2. Thermal Action

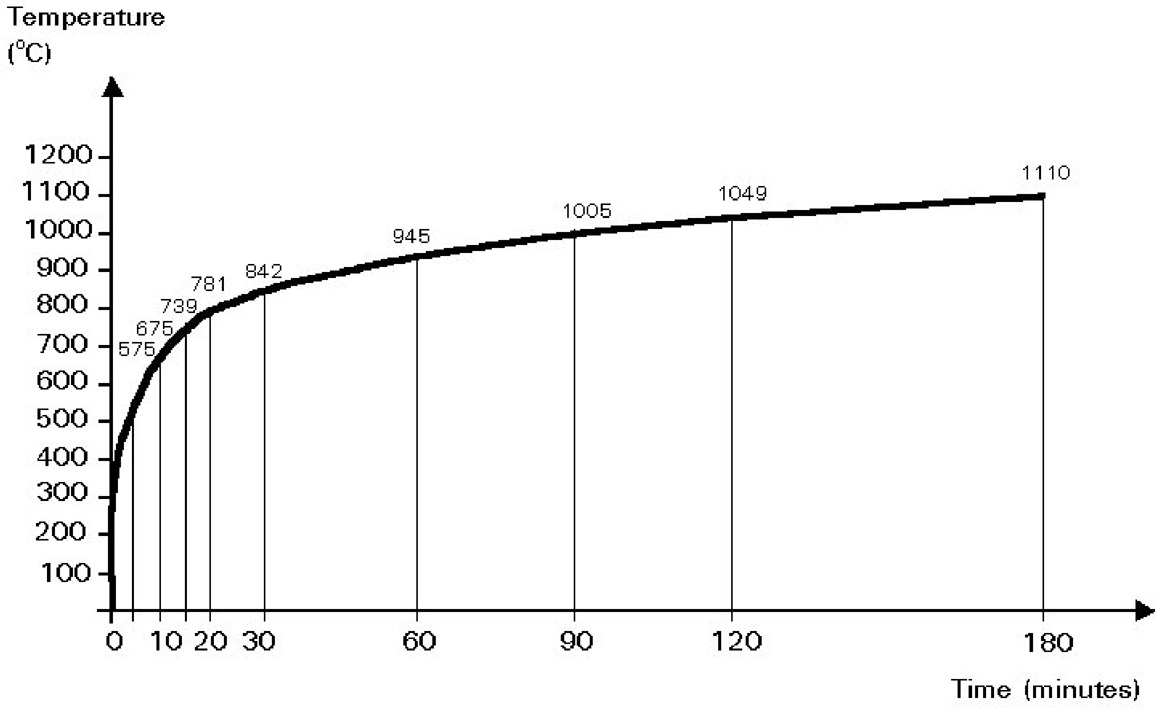
Thermal Actions represent the action of fire on the structure. The different possibilities of thermal actions are given in Eurocode 1-2 (EN 1991-1-2:2005). Sometimes the requirement may be prescriptive and define both the time – temperature curve and the time of resistance of the curve

Nominal Temperature –time curves

Temperature time curves are analytical functions that give the temperature as a function of time. Nominal curves do not represent a real fire. They have to be considered as arbitrary functions. These curves are used in a prescriptive regulative environment. Eurocode 1-2 (EN 1991-1-2:2005) proposes 3 nominal temperature–time curves.

- The Standard Temperature Time curve also referred to as the ISO curve. It is used to represent a fully developed fire in a compartment. The equation is given by

$$\theta_g = 20 + 345\log_{10}(8t+1)$$



ISO standard fire curve (image: www.fgg.uni-lj.si)

- The External Time Temperature curve is used for the outside surfaces of the separating external wall which are exposed to fire. These are used for the façade and should not be used for calculating the loads on any external load bearing structures.

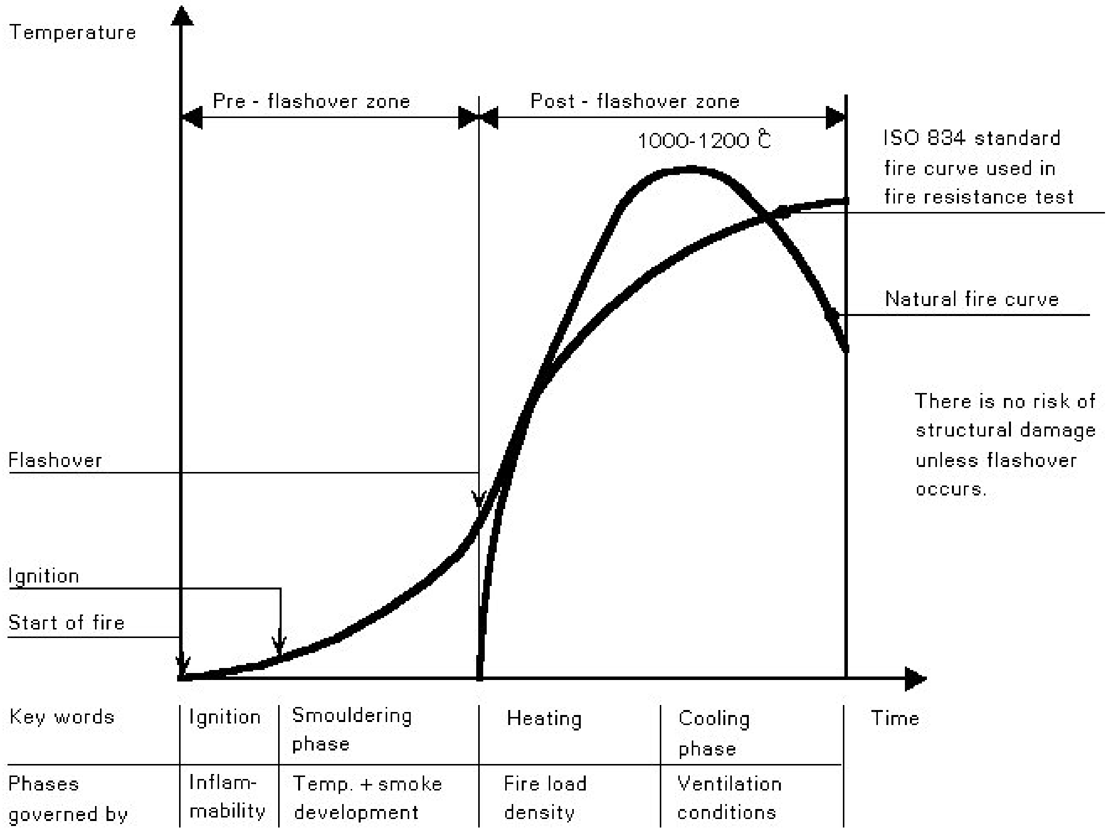
$$\theta_g = 20 + 660(1 - 0.687e^{-0.32t} - 0.313e^{-3.8t})$$

- The Hydrocarbon time temperature curve is used for representing effects of a hydrocarbon type of fire.

$$\theta_g = 20 + 1080(1 - 0.325e^{-0.167t} - 0.675e^{-2.5t})$$

Parametric Temperature – time curves

- Parametric temperature time curves give the evolution of gas temperatures as a function of time in a compartment. They are based on parameters that represent the important physical phenomenon that influence the growth of fire in a compartment. They are described in the Annex A of Eurocode 1.



Development of Natural Fire (image: www.fgg.uni-lj.si)

2.2.3. Temperature in Members

The increase in temperature of the steel member depends on the temperature of the compartment, the area of steel exposed to the fire and the fire protection applied. The heat transfer from the hot gases into the surface of structural elements by radiation and convection is treated as a boundary condition. The heat transfer within a structural element is by conduction. Simplified methods for heat transfer have been developed.

Section factor

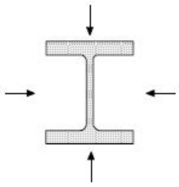
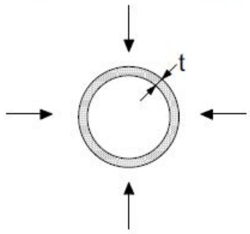
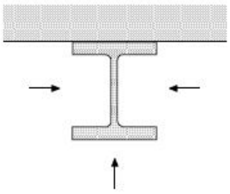
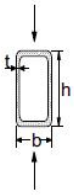
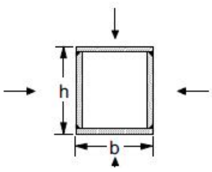
The rate of rise in temperature of the member depends on its mass and surface area exposed to fire. Section factor or massivity factor governs the rate of temperature rise and is the ratio of surface area exposed to the heat flux and the volume of the member per unit length.

Eurocode 3 (EN 1993-1-2:2005) defines the section factor as A_m/V for unprotected members. For prismatic members with boundary conditions that are constant along the length the temperature, the section factor is defined as the ratio of perimeter of section exposed to fire and the area of cross section of the member

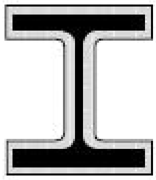
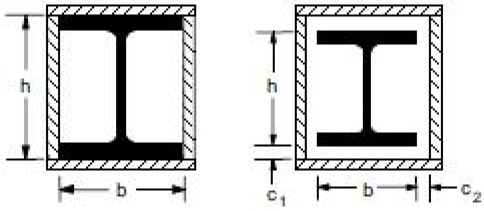
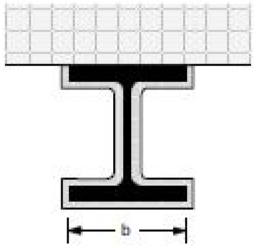
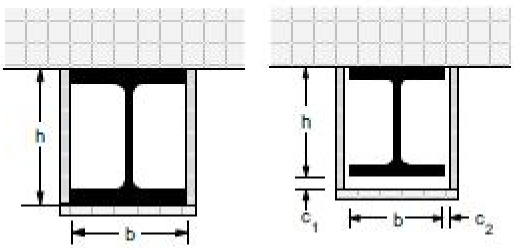
$$\frac{A_m}{V} = \frac{P*l}{A*l} = \frac{P}{A}$$

The rate at which the section will heat up depends directly on the surface area and inversely proportional to the mass or volume of the member. The smaller the section factor, the slower the member heats up.

Definition of section factor for unprotected steel members- EN1993-1-2:2005

<table>
<tr>
<td>Open section exposed to fire on all sides:
$\frac{A_m}{V} = \frac{\text{perimeter}}{\text{cross-section area}}$
</td>
<td>Tube exposed to fire on all sides: $A_m/V = 1/t$
</td>
</tr>
<tr>
<td>Open section exposed to fire on three sides:
$\frac{A_m}{V} = \frac{\text{surface exposed to fire}}{\text{cross-section area}}$
</td>
<td>Hollow section (or welded box section of uniform thickness) exposed to fire on all sides:
If $t \ll b$: $A_m/V \approx 1/t$
</td>
</tr>
<tr>
<td colspan="2">Welded box section exposed to fire on all sides:
$\frac{A_m}{V} = \frac{2(b+h)}{\text{cross-section area}}$
If $t \ll b$: $A_m/V \approx 1/t$
</td>
</tr>
</table>

Definition of section factor for unprotected steel members (EN 1993-1-2:2005)

Sketch	Description	Section factor (A_p/V)
	Contour encasement of uniform thickness	$\dfrac{\text{steel perimeter}}{\text{steel cross-section area}}$
	Hollow encasement of uniform thickness)[1]	$\dfrac{2(b+h)}{\text{steel cross-section area}}$
	Contour encasement of uniform thickness, exposed to fire on three sides	$\dfrac{\text{steel perimeter} - b}{\text{steel cross-section area}}$
	Hollow encasement of uniform thickness, exposed to fire on three sides)[1]	$\dfrac{2h+b}{\text{steel cross-section area}}$

)[1] The clearance dimensions c_1 and c_2 should not normally exceed $h/4$

Temperature of unprotected steel work exposed to fire:

Eurocode 3 (EN 1993-1-2:2005) provides a simple equation for calculating the thermal response of unprotected steel members. Assuming an equivalent uniform temperature distribution throughout the cross section, the temperature rise in an unprotected steel member during a time interval is given by,

$$\theta_{a,t} = k_{sh} \frac{A_m/V}{c_a \rho_a} \dot{h}_{net,d} \Delta t$$

k_s = correction factor for shadow effect

c_a = specific heat of steel

$\dot{h}_{net,d}$ = design value of net heat flux per unit area.

$\dot{h}_{net,d}$ is the sum of convective part $\dot{h}_{net,c}$ and a radiative part $\dot{h}_{net,r}$

$$\dot{h}_{net,r} = \dot{h}_{net,c} + \dot{h}_{net,r}$$

Where,

$$\dot{h}_{net,c} = \alpha_c(\theta_g - \theta_m)$$

α_c = coefficient of heat transfer by convection

θ_g = gas temperature of the fire compartment

θ_m = surface temperature of the steel member

The assumption is that the initial temperature of the member is 20 C.

For rectangular or circular hollow sections, fully embedded in fire the effect does not play any role and k_{sh} is taken as unity. For I sections under nominal fire actions the correction factor for the shadow effect may be determined from

$$k_{sh} = 0.9[A_m/V]_b/[A_m/V]$$

$[A_m/V]_b$ =box value of the section factor. It is the ratio of between the exposed surface area of a notional bounding box to the section and the volume of steel.

In all other cases, the value of k_{sh} shall be taken as

$$k_{sh} = [A_m/V]_b/[A_m/V]$$

Temperature of unprotected steel in °C exposed to ISO 834 fire curve for different values of $k_{sh}\frac{A_m}{V}$ (Fire Design of Steel structures)

Time (min)	45
$k_{sh}\frac{A_m}{V}$	Temp
m^{-1}	^oC
10	409
15	537
20	628
25	692
30	728
40	761
60	852
100	889
200	897
300	899
400	900

1.2.4. Mechanical Analysis

Under elevated temperature, the steel stress – strain behaviour becomes highly nonlinear and the also thermal expansion with restraint adds additional restraint forces. This makes the design derived from ambient temperature inaccurate under fire situation. The basic principles of fire design of steel structures are defined in Eurocode 3 (EN 1993-1-2: 2005) and Eurocode 4 (EN 1994-1-2: 2005) for composite structures. Where mechanical resistance to fire is required, structures should be designed and constructed in such a way that they maintain their load bearing function during the fire exposure (Franssen, J-M:2010). According to EN 1991 -1-2:2002, the mechanical analysis shall be performed for the same duration as used in the temperature analysis and the verification of fire resistance of individual members can be performed in one of the 3 domains

1. In the time domain

$$t_{fi,d} \geq t_{fi,reqd}$$

2. In the strength domain

$$E_{fi,d,t} \geq R_{fi,d,t} \text{ at time } t_{fi,reqd}$$

3. In the temperature domain

$$\theta_d \geq \theta_{cr,d} \text{ at time } t_{fi,reqd}$$

$t_{fi,d}$ = design value of fire resistance or the failure time

$t_{fi,reqd}$ = required fire resistance time

$E_{fi,d,t}$ = design value of relevant effects of actions in the fire situation at time t. It is assumed to be constant during the fire, $E_{fi,d}$

$R_{fi,d}, t$ = design value of the resistance of the member in the fire situation at time t.

θ_d = design value of steel temperature

$\theta_{cr,d}$ = design value of critical temperature or the collapse temperature

Eurocode states that for verifying standard fire resistance requirements, a member analysis is sufficient. There are 3 different assessment models to determine resistance of a structure or a single element

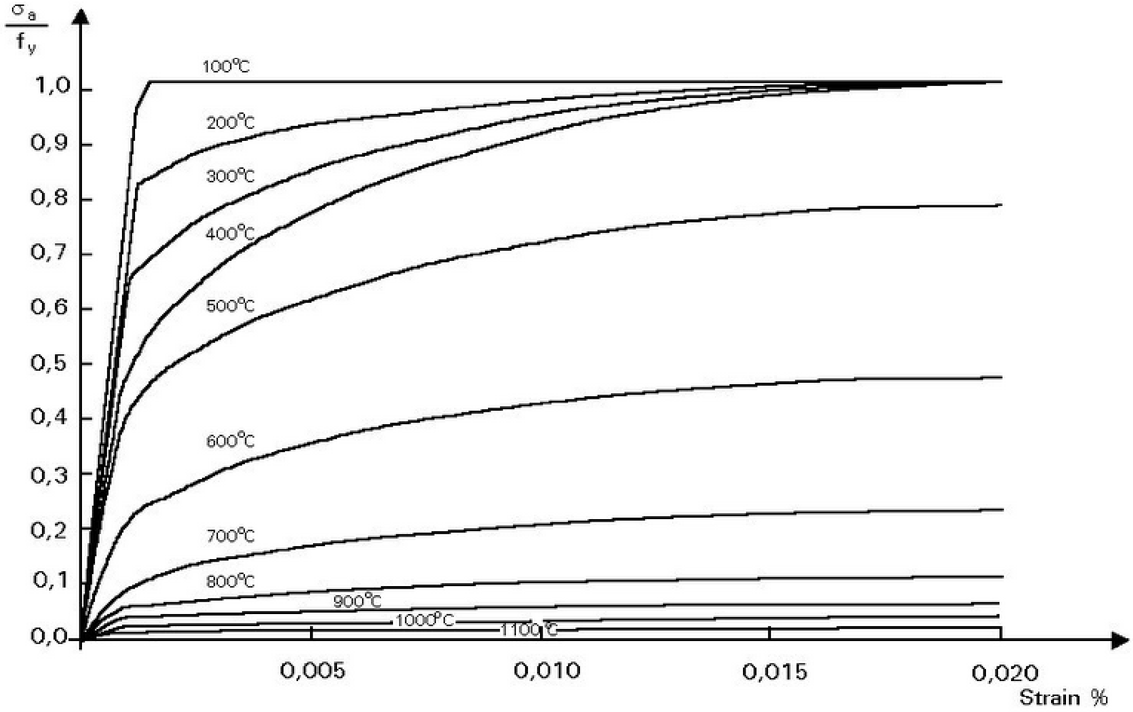
1. Tabulated data – These are obtained from tests in standard furnaces, empirical methods or numerical calculations. They are widely used for composite structures.
2. Simple calculation model – Simple analytical formulae are used for isolated members
3. Advanced Calculation models

Simple calculation model is used for this project.

Mechanical Properties of Carbon Steel

Carbon steel begins to lose strength above 400 ^oC. (Wang, Y.C.:2013).

At elevated temperature, the behaviour of steel is an elastic-elliptic-perfectly plastic model followed by a linear descending branch introduced at large strains when the steel is used as material in advanced calculations models.



Stress strain relationship for S235 steel at elevated temperature

(image: www.fgg.uni-lj.si)

The stress strain relationship at elevated temperature is characterised by 3 parameters

- The Limit of proportionality $f_{p,\theta}$
- The effective yield strength $f_{y,\theta}$
- The Young's modulus $E_{a,\theta}$

Design values for the mechanical properties in the fire situation are obtained as

$$X_{d,fi} = k_\theta X_k / \gamma_{M,fi}$$

k_θ = reduction factor of strength or deformation property. It depends on the temperature of the material

X_k = Characteristic value of strength or deformation property at ambient temperature.

$\gamma_{M,fi}$ = partial safety factor for the relevant material property for the fire situation, taken as 1.

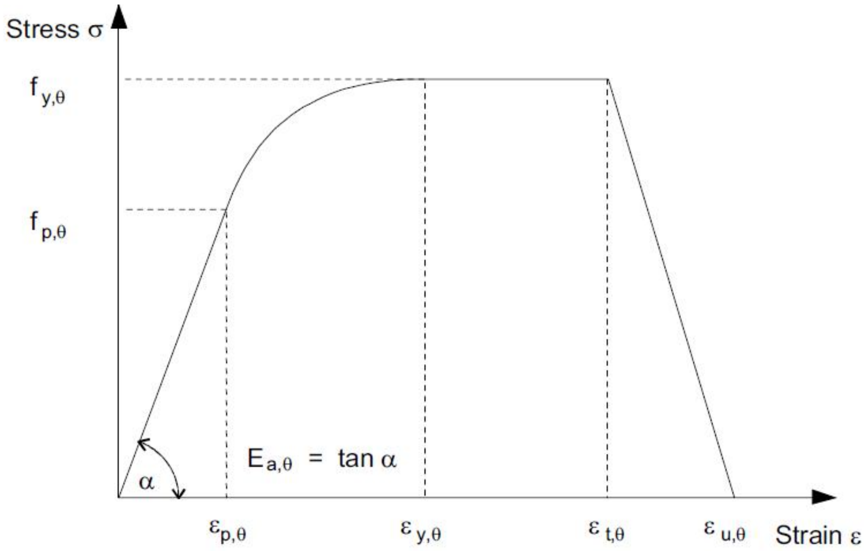


Fig: Stress – strain relationship for carbon steel at elevated temperature (EN 1993-1-2:2005)

As per above equation, the strength at temperature θ is a function of the yield strength f_y at 20° C given by

$$f_{y,\theta} = k_{y,\theta} f_y$$

The Young's modulus is a function of E_a at 20 C

$$E_{a,\theta} = k_{E,\theta} E_a$$

The proportional limit at elevated temperature is given by

$$f_{p,\theta} = k_{p,\theta} f_y$$

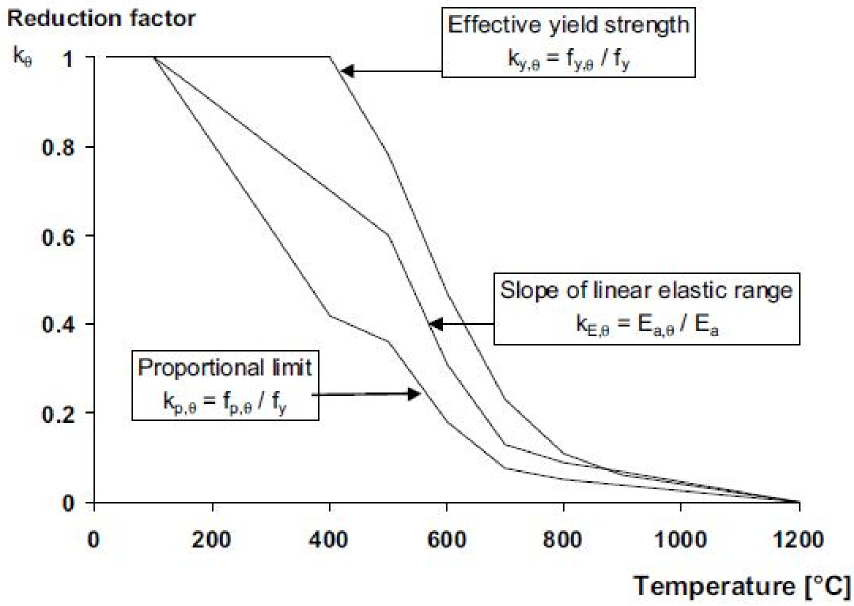
The reduction of the effective yield strength was obtained experimentally and can be approximated by the following equation

$$k_{y,\theta} = \left\{ 0.9674 \left(e^{\frac{\theta_a - 482}{39.19}} + 1 \right) \right\}^{-1/3.833} \leq 1$$

Reduction factors for stress-strain relationship of carbon steel at elevated temperatures (EN 1993-1-2:2005)

Steel Temperature θ_a	Reduction factors at temperature θ_a relative to the value of f_y or E_a at 20°C		
	Reduction factor (relative to f_y) for effective yield strength $k_{y,\theta} = f_{y,\theta}/f_y$	Reduction factor (relative to f_y) for proportional limit $k_{p,\theta} = f_{p,\theta}/f_y$	Reduction factor (relative to E_a) for the slope of the linear elastic range $k_{E,\theta} = E_{a,\theta}/E_a$
20°C	1,000	1,000	1,000
100°C	1,000	1,000	1,000
200°C	1,000	0,807	0,900
300°C	1,000	0,613	0,800
400°C	1,000	0,420	0,700
500°C	0,780	0,360	0,600
600°C	0,470	0,180	0,310
700°C	0,230	0,075	0,130
800°C	0,110	0,050	0,090
900°C	0,060	0,0375	0,0675
1000°C	0,040	0,0250	0,0450
1100°C	0,020	0,0125	0,0225
1200°C	0,000	0,0000	0,0000

NOTE: For intermediate values of the steel temperature, linear interpolation may be used.

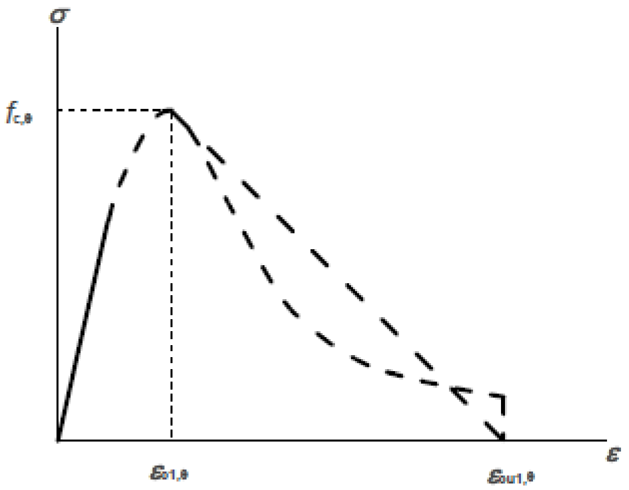


Reduction factors for the stress-strain relationship of carbon steel at elevated temperatures (EN 1993-1-2:2005)

Mechanical Properties of Concrete

Concrete loses its properties at higher temperatures. (Wang, Y.C.:2013)

The stress-strain curves at higher temperatures for concrete differ significantly from that of steel



Mathematical model for stress-strain relationships of concrete under compression at elevated temperatures temperatures (EN 1992-1-2:2004)

The initial curvilinear part is obtained from the equation

$$\sigma_{c,\theta} = f_{c,\theta}\left[3\left(\frac{\varepsilon_{c,\theta}}{\varepsilon_{cu,\theta}}\right)/\left\{2+\left(\frac{\varepsilon_{c,\theta}}{\varepsilon_{cu,\theta}}\right)^3\right\}\right]$$

According to Eurocode, it is sufficient to perform member analysis for verifying standard fire resistance requirements.

1.2.5. Fire resistance of Steel Members

Tension Members

The design value of the tension force in the fire situation should satisfy the following condition at each cross section (Franssen, J-M:2010),

$$\frac{N_{fi,Ed}}{N_{fi,\theta,Rd}} \leq 1.0$$

where

$$N_{fi,\theta,Rd} = k_{y,\theta} N_{Rd} \left[\gamma_{M0} / \gamma_{M,fi}\right]$$

γ_{M0} = partial safety factor for the material of cross section

N_{Rd} = Design resistance of the cross section $N_{pl,Rd}$ for normal temperature design

$$N_{pl,Rd} = \frac{Af_y}{\gamma_{M0}}$$

Compression Members

Design compression force in the fire situation, $N_{b,fi,Ed}$ at each cross section should satisfy the following condition

$$\frac{N_{b,fi,Ed}}{N_{b,fi,t,Rd}} \leq 1.0$$

Where design buckling resistance $N_{b,fi,t,Rd}$, at time *t* of a compression member with Class 1, Class2 or Class3 cross section with a uniform temperature θ_a should be determined from

$$N_{b,fi,t,Rd} = \chi_{fi} A k_{y,\theta} f_y / \gamma_{M,fi}$$

$K_{y,\theta}$ = reduction factor for the yield strength of steel at uniform temperature θa, reached a time t

χ_{fi} = reduction factor for flexural buckling in the fire design situation

χ_{fi} is taken as the lower of the values of $\chi_{y,fi}$ and $\chi_{z,fi}$ determined as

$$\chi_{fi} = \frac{1}{\phi_\theta + \sqrt{\phi_\theta^2 - \bar{\lambda}_\theta^2}}$$

Where

$$\phi_\theta = \frac{1}{2}\left[1 + \alpha\bar{\lambda}_\theta + \bar{\lambda}_\theta^2\right]$$

Imperfection factor α is given by

$$\alpha = 0.65\sqrt{235 / f_y}$$

Non dimensional slenderness $\bar{\lambda}_\theta$ for the temperature θ_a is given by

$$\bar{\lambda}_\theta = \bar{\lambda}\sqrt{k_{y,\theta} / k_{E,\theta}}$$

Where $\bar{\lambda}$ = non dimensional slenderness at room temperature.

$$\bar{\lambda} = \frac{\lambda}{\lambda_1}$$

λ = member slenderness evaluated with the buckling length in fire situation, l_{fi}

$$\lambda = \frac{l_{fi}}{i}$$

i = radius of gyration

$$\lambda_1 = \pi\sqrt{\frac{E}{f_y}}93.9\varepsilon$$

$$\varepsilon = \sqrt{\frac{235}{f_y}} \quad (f_y \; in \; N/mm^2)$$

The buckling length should be determined as for the normal temperature design. In case of braced frame, the buckling length of a continuous column may be determined by considering it as fixed to the fire compartments above and below. The fire resistance of the the building component should not be less than the fire resistance of the column.

l_{fi} = 0.5L in the intermediate storey and 0.7L in the top storey for a braced frame

2.2.6. Fire resistance of Composite Member

Check for composite beam

The fire design of steel and concrete composite structures with partially or fully encased steel elements is covered in EN 1994-1-2. Slabs are assumed to be heated from the bottom, columns from all four sides and beams from 3 sides if trapezoidal sheeting covers atleast 85% of the upper flange of the beam. There are 2 methods to evaluate composite structures (Wang, Y.C.:2013).

1. Critical temperature method

It is only applicable to symmetric cross sections of a maximum depth 500mm and a minimum slab 120 mm. The temperature of the steel cross section is assumed to be uniform. In the method the critical temperature θ_{cr} can be determined from the load level $\eta_{fi,t}$ applied to the cross section and the strength of steel without calculating the bending resistance of the cross section. The critical temperature is a function of the load level in the fire design at time t:

$$\eta_{fi,t} = \frac{E_{fi,d,t}}{R_d} = \frac{\eta_{fiEd}}{R_d} = \frac{R_{fidt}}{R_d}$$

The ultimate limit state is reached when the design resistance in the fire situation, $R_{fi,d,t}$ has decreased to the level of fire action, $E_{fi,d,t}$. The load level may be used to find the required steel yield strength at elevated temperatures:

$$\eta_{fi,t} = \frac{R_{fi,d,t}}{R_d} = \frac{f_{a\max,\theta cr}}{\frac{f_{ay,20^oC}}{\gamma_M}} \cong \frac{f_{a\max,\theta cr}}{f_{ay,20^oC}}\frac{1}{0.9}$$

2. Bending moment resistance method

When using plastic analysis, the composite section is divided into different sections of uniform temperature. If the plastic neutral axis is in the concrete slab, the resultant tension force is from the steel cross-section.

$$T = \left[f_{a\max,\theta 1}(b_1 e_1) + f_{a\max,\theta w}(h_w e_w) + f_{a\max,\theta 2}(b_2 e_2) \right] / \gamma_{M,fi,a}$$

The thickness of compressive zone in the concrete I given as

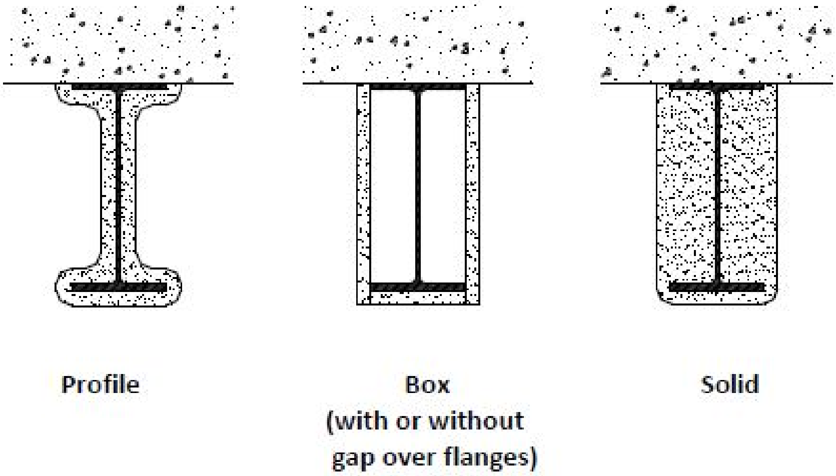
$$h_u = T / (b_{eff} \, f_{c,20^o C} / \gamma_{m,fi,c})$$

The bending resistance is

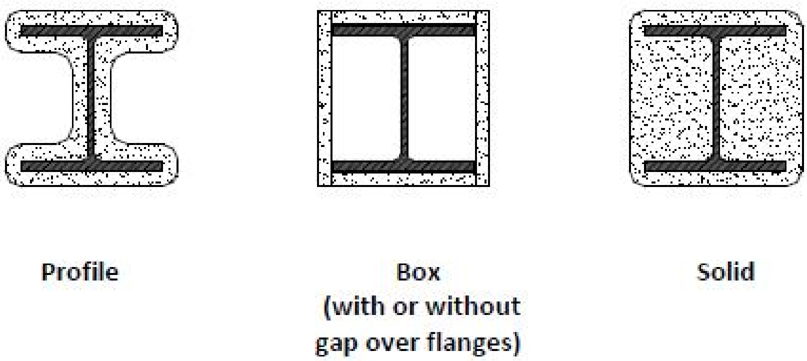
$$M_{fi,Rd^+} = T(y_F - y_T)$$

2.2.7. Methods of Fire Protection

A wide range of materials are now available to improve the fire resistance of structural steel members. They can be applied in a different ways to meet specific site requirements. They can differ as profile, box or solid methods of application. Sprayed materials would normally be applied to follow the profile of the section. Board materials would normally be used to form a box around the section and concrete can be used to form solid protection.



Protection technique for three-sided protection (Yellow book, 2013)



Protection technique for four-sided protection (Yellow book, 2013)

Spray Protection

They are a form of plaster in the form of slurry which can be pumped and dispersed onto building structures by compressed air at he spray nozzle. They contain fibres, gypsum or Portland cement and other binders.

Advantages

- Cheaper
- Can be applied to all shapes
- Good for thermal and acoustic insulation
- Can provide resistance up to 240 minutes

Disadvantages

- Only suitable for steel members out of site
- Application process is messy
- They can be easily damage
- It is difficult to ensure uniform thickness
- Wire reinforcement may be required for larger member
- More space is required for given protection
- Not visually pleasing

Boarding

Boarding fire-protection solutions are a clean dry process. They provide a neat aesthetic finish with the required fire performance. However they are impractical for the protection of castellated beams or the increasing used cellular beams where the holes are used for services penetrations.

Advantages

- Clean and dry installation
- Good finish
- Up to 240 minutes fire performance
- Pre-formed sections are available

Disadvantages

- They are not so good on complex shapes
- Application time is long
- Thickness at higher performance can be an issue
- Weight can be also be high with dense boards

Intumescent Paint

Intumescent coatings provide an appearance similar to that of a paint finish. At normal temperatures, they remain stable. But in the event of a fire, the increase in temperature causes a chemical reaction and intumescent coating expands to many times its original thickness. This provides an insulating foam-like coating or "char" which protects the substrate.

Advantages

- Ideal for the exposed profile of the steel
- Suitable for castellated and cellular beams where the holes are used for services

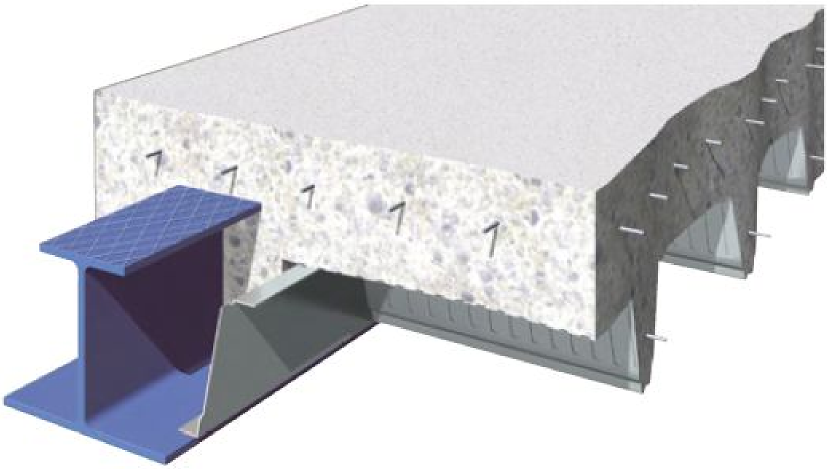
- Light weight
- Up to 10 times faster to apply than boarding systems
- It is fibre free, hence no dust
- Easy to clean and maintain
- Thin film system reduces the amount of space used

Disadvantages

- Skilled application is required for application
- Quality checks are important
- Primer compatibility is necessary to be checked
- Site over-spray issues may occur
- Masking may be required to surrounding areas

Slim Floor

The upper flange plates and cores of the beams are incorporated in the thickess of the concrete slabs. The fire resistance is achieved since only the lower flange of the beam is exposed to the fire.



Typical Asymmetric Slimflor® Beam ***(www.tatasteelconstruction.com)***

Sprinklers

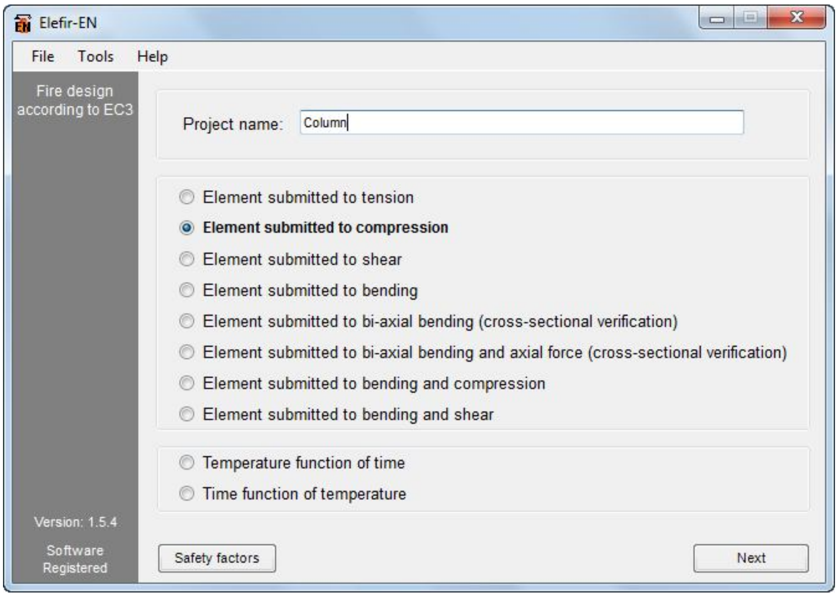
These are active fire protection systems and reduce the temperature of steel members in the event of a fire.

2.2.8. Software – Elefir EN

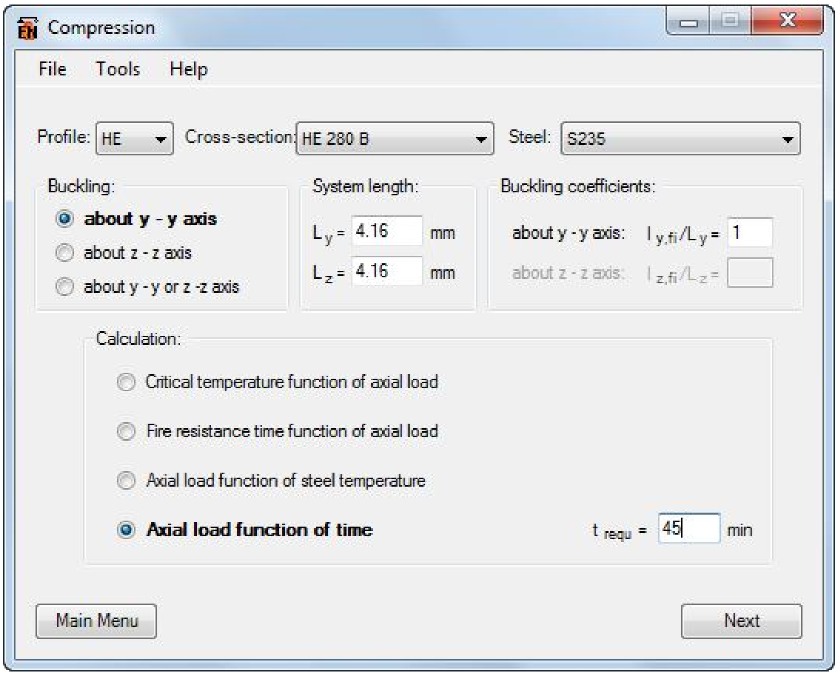
This computer program has been developed for the fire design of structural steel members in accordance with the simple calculation model given in the Eurocodes. The computer program Elefir was developed in the late 1990’s at the University of Liege,Belgium. It was based on the simplified fire design rules given in the ENV versions of the Eurocode 1 and Eurocode 3. The University of Aveiro has updated this software so that it in alignment with the new versions of the Eurocodes. This updated version of the software is called Elefir-EN (Franssen, J-M:2010).

Elefir-EN allows the user to calculate the fire resistance of simple steel members loaded about the strong axis or about the weak axis. Calculations can be performed in the time domain, resistance domain and temperature domain.

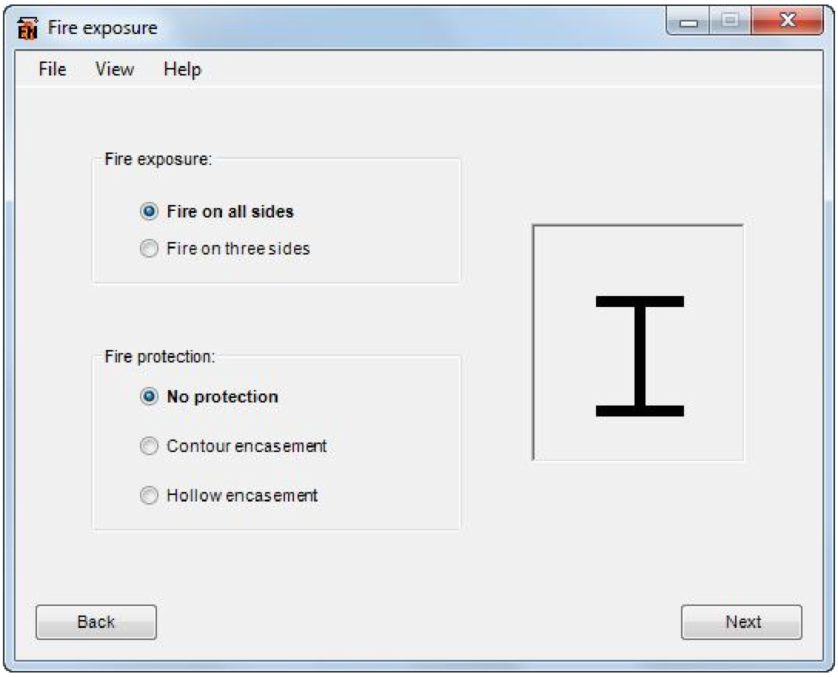
– The type of element is chosen



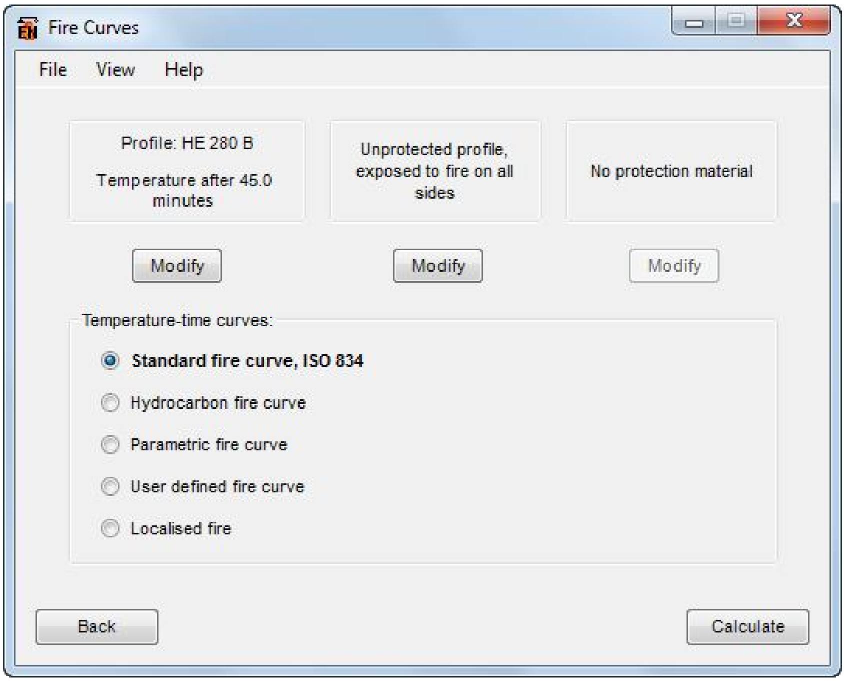
– Details about the element dimensions and the type of analysis is chosen



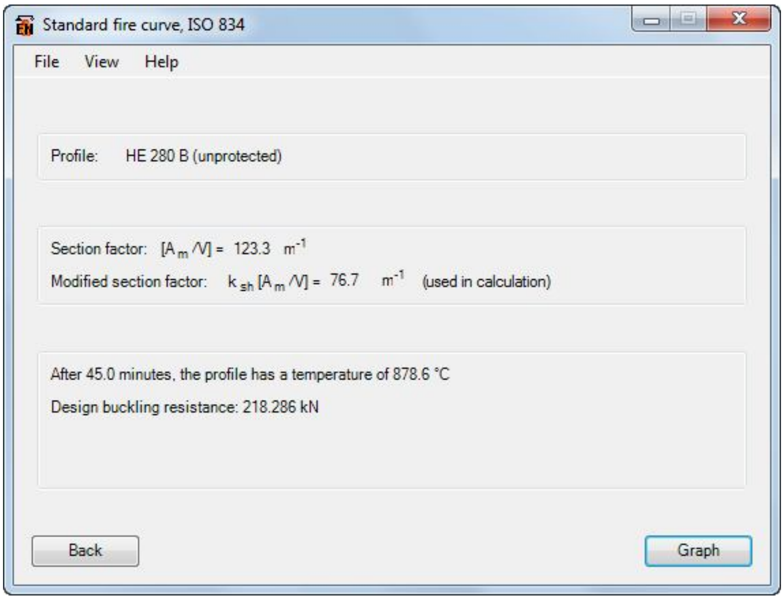
– Choose the option for fire exposure. The section factor gets introduced directly.
– Options for fire protection is also chosen



– Select the heating curve. It could be ISO 834 curve, the hydrocarbon curve, the parametric curve, user defined curve or localized fires impacting or not impacting the ceiling.



– In our study we will use the standard fire curve, ISO 834. The results for the analysis will be obtained as below.

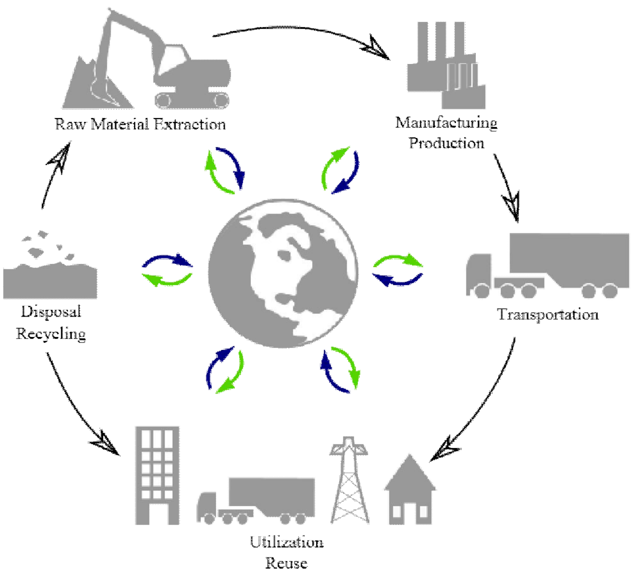


1.3. Sustainability

1.3.1. Introduction

ISO 14040 defines Life Cycle Analysis as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle". Life Cycle Analysis is a tool to evaluate the environmental burden of products in all stages of their life cycle. The different stages include the extraction of resources, production of the materials, parts and the product itself, the use stage, to the stages at the end of life which may be recycling or final disposal (Gervásio, H. et al, 2014)

LCA identifies and quantifies material usage, energy requirements, solid wastes, and atmospheric and waterborne emissions throughout the product life cycle i.e. from raw material acquisition to end-of-life.

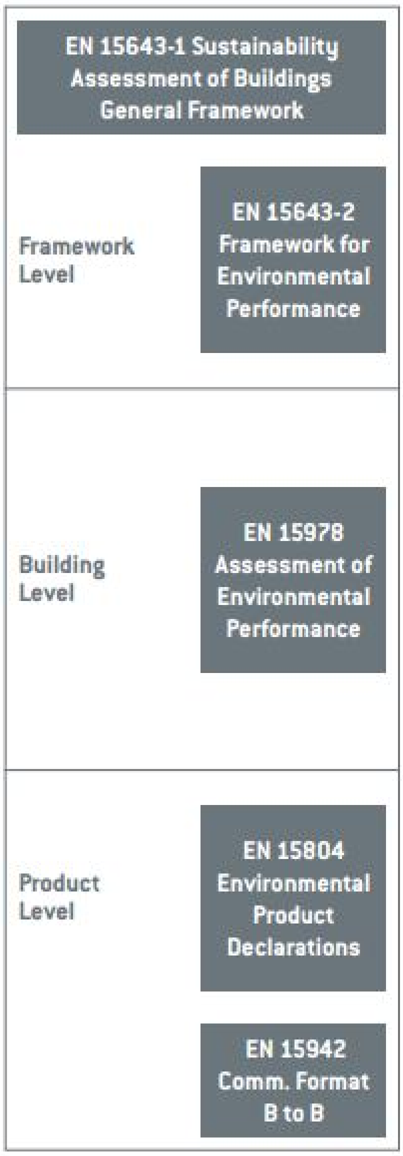


Life Cycle Assessment of a building (www.westwindhardwood.com)

1.3.2. Methodologies for Building sustainability assessment

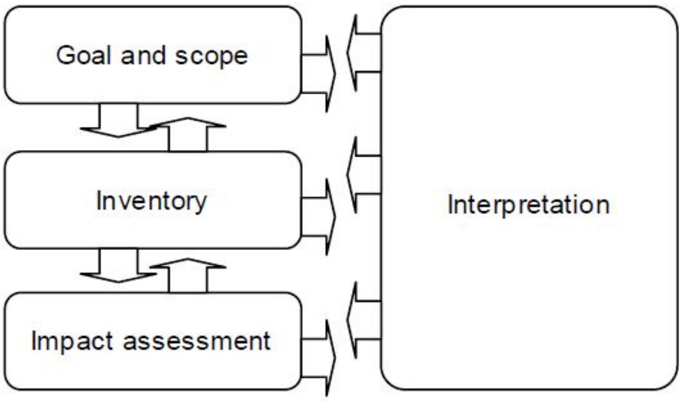
The construction industry has a huge environmental impact in the industrial sector. Hence it is important to work on the environmental assessment of the built environment. At present there are 2 major types of assessment tools.

- Qualitative – they are based on criteria and scores. They are called rating systems as they are based on assigning points to predefined parameters and auditing of buildings. Eg : LEED in the US, BREAM in the UK etc.
- Tools based on Life cycle approach. It uses a quantitative analysis of inputs and outputs.



2.3.3. Framework for Life Cycle Assessment

International Standards ISO 14040 (2006) and ISO 14044 (2006) specify the framework for performing life cycle assessment studies. A life assessment should include the goal and scope, inventory analysis, impact assessment and interpretation of results. The different phases may sometimes be interrelated and thus the analysis becomes iterative.



LCA general framework (ISO 14044:2006)

European standards for life cycle assessment of buildings

The European Committee for Standardization (CEN) was formed for the development of horizontal standardised methods for the assessment of the integrated environmental performance of buildings.

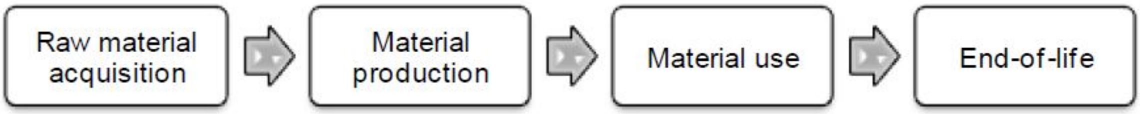
The CEN Technical Committee 350 develops standards, technical reports and technical specifications to provide methodology and indicators for the sustainability assessment of buildings.

The life cycle environmental approach adopted in this project follow the two standards dedicated to the evaluation of the environmental impacts of buildings: the EN 15978 (2011) and the EN 15804 (2012), for the building and material levels, respectively.

2.3.4. Building level (EN 15978, 2011)

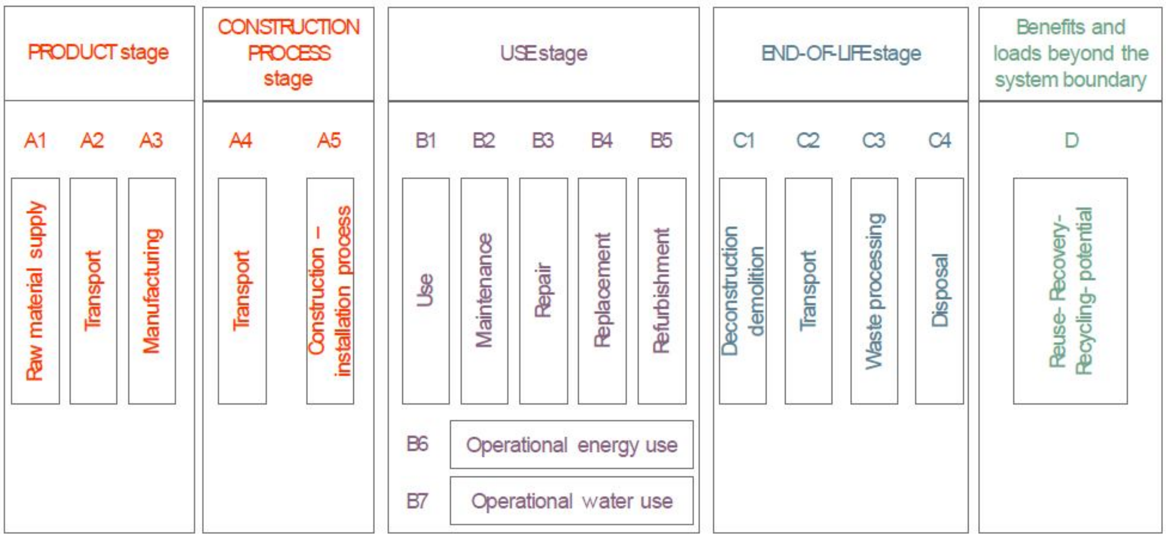
Life Cycle Stages

The system boundaries determine which processes or life stages are included within the LCA.



Processes included in a LCA of a generic material (credits to background document)

When only the initial stages are included, the LCA is called a cradle to Gate analysis. If the complete cycle, from raw materials to end of life in included, then it is called cradle to grave. When recycling processes are performed at the end of life which avoids the production of new materials, then it is called cradle to cradle analysis.



<u>1. Product Stage</u>

The product stage includes the A1 to A3. The system boundary includes the processes that provide the material and energy inputs into the system, manufacturing, and transport processes up to the factory gate and also the processing of any waste arising from those processes. This stage includes:

A1 – Raw Material Supply

A2 – Transportation to the manufacturer

A3 - Manufacturing.

<u>Construction Stage</u>

The construction process stage includes the information modules for:

A4 - Transportation to the building site

A5 - Installation in the building.

Use Stage

The use stage includes two types of information modules. Modules related to the building fabric (modules B1-B5) and modules related to the operation of building (modules B6-B7):

B1 - use or application of the installed produc;
B2 - Maintenance
B3 - Repair
B4 - Replacement
B5 - Refurbishment
B6 - Energy use to operate building integrated technical systems,
B7 - Operational water use by building integrated technical systems

End of Life Stage

The end-of-life stage of the building includes all outputs that have reached the "end-of-waste" state, resulting from dismantling, deconstruction or demolition of the building

C1 - Deconstruction, demolition
C2 - Transportation to waste processing
C3 - Waste processing for reuse, recovery and/or recycling
C4 - Waste disposal

Module D

Information module D includes all the net benefits or loads resulting from reusable products, recyclable materials and/or useful energy carriers leaving a product

Impact Assessment

For the stage of life cycle impact assessment, two types of environmental categories are considered according to EN 15978: environmental indicators describing environmental impacts and environmental indicators describing input and output flows. Both types of indicators are indicated in the following paragraphs.

Indicators describing environmental impacts (EN15978, 2011)

Indicator	Unit
Global warming potential, GWP	kg CO_2 equiv
Depletion potential of the stratospheric ozone layer, ODP;	kg CFC 11 equiv
Acidification potential of land and water; AP;	kg SO^{2-} equiv
Eutrophication potential, EP;	kg $(PO_4)^{3-}$ equiv
Formation potential of tropospheric ozone photochemical oxidants, POCP;	kg Ethene equiv
Abiotic Resource Depletion Potential for elements; ADP_elements	kg Sb equiv
Abiotic Resource Depletion Potential of fossil fuels ADP_fossil fuels	MJ

Global warming potential (GWP)

Greenhouse gases are infrared active gases, which are present in the earth's atmosphere. They absorb the radiation leaving the earth and reflect some of the heat back to the earth contributing to warm the surface. But since the in industrial period, the concentration of these greenhouse gases has risen much higher and has led to Global Warming. Different GHGs contribute to global warming differently.

GWP is the relative measure of CO_2 which would be needed to be release in order to have the same radiative forcing effect as 1 kg of the GHG over a particular period of time.. The unit is kg CO_2 eq.

GWPs for given time horizons (in kg CO2 eq./kg) (IPCC, 2007)

	20 years	100 years	500 years
Carbon Dioxide (CO_2)	1	1	1
Methane (CH_4)	62	25	7
Nitrous oxide (N_2O)	275	298	156

The determination of the indicator Global Warming is given by

$$Global\ Warming = \sum_i GWP_i * m_i$$

m_i = mass of the substance released (in kg)
The unit of expression is kg CO_2 equivalent
In the following study, the time horizon of 100 years is considered.

Ozone Depletion Potential (ODP)

The Ozone layer prevents the ultraviolet radiations from entering the earth's atmosphere. The ozone depleting gases release free radical molecules which breakdown the ozone. This depletion of the ozone layer results in health problem like skin cancer, cataracts and damage to animals and crops.
The major ozone depleting gases are CFC, HCFC and halons.
ODP is defined as the global loss of ozone due to the substance in relation to the global loss of ozone due to the reference substance. The reference unit is kg CFC-11 equivalent. OPD's assuming steady state are indicated in the table for selected substances.

OPDs for some substances (in kg CFC-11 eq./kg) (Heijungs et al., 1999)

	Steady-state ($t \approx \infty$)
CFC-11	1
CFC-10	1.2
Halon 1211	6.0
Halon 1301	12.0

The determination of the indicator Ozone depletion is given by

$$Ozone\ Depletion = \sum_i ODP_i * m_i$$

m_i = mass of the substance released (in kg)
The unit of expression is kg CFC-11 equivalent

Acidification Potential (AP)

Acidification is the process where compounds like Ammonia, Sulphur dioxide and nitrogen oxides are converted to acids. These acidic particles when falls on the ground as rain causes considerable damage to the ecosystem. AP is measured relative to an equivalent release of SO2.

Acidification potentials (in kg SO2 eq.) (Huijbregts, 2001)

	Ammonia (NH_3)	Nitrogen Oxide (NO_x)	Sulfur Dioxide (SO_2)
APi	1.60	0.50	1.20

The determination of the indicator acidification is given by

$$Acidification = \sum_i AP_i * m_i$$

m_i = mass of the substance released (in kg)
The unit of expression is kg $_{SO2}$ equivalent

Eutrophication Potential (EP)

Eutrophication can be defined as the overenrichement of water courses. It can lead to damage of ecosystems, increased mortality of aquatic life and to loss of life forms that are dependent on low nutrient environments.

EP is measured using the reference unit of kg nitrogen or phosphate equivalents. Taking phosphate as the reference, the characterisation factors for selected substances are given in the below table.

Eutrophication potentials (in kgPO_4^{3-} eq.) (Heijungs et al., 1999)

	Ammonia (NH_3)	Nitrogen Oxide (NO_x)	Nitrate (N)	Phosphate (P)
EPi	0.35	0.13	0.10	1.00

The determination of the indicator eutrophication is given by

$$Eutrophication = \sum_i EP_i * m_i$$

m_i = mass of the substance released (in kg)
The unit of expression is $kgPO_4^{3-}$ equivalent

Photochemical Ozone Creation Potential (POCP)

Low level ozone is implicated in impacts such as damage to crops and asthma and other respiratory complaints in humans. POCP is a measure of the relative ability of a substance to produce ozone in the presence of NO_x and sunlight, POCP is expressed using the reference substance ethylene. Characterisation factors for POCP have been developed using United Nations Economic Commission for Europe (UNECE) trajectory model.

POCP were calculated for 2 scenarios

- A scenario with relatively high background concentration of NO_x
- A scenario with relatively low background concentration of NO_x

POCPs for different concentration of NO_x and for some substances (in kg C2H4 eq./kg) (Heijungs et al., 1999)

	High-NO_x POCPs	Low-NO_x POCPs
Acetaldehyde (CH_3CHO)	0.641	0.200
Butane (C_4H_{10})	0.352	0.500
Carbon monoxide (CO)	0.027	0.040
Ethyne (C_2H_2)	0.085	0.400
Methane (CH_4)	0.006	0.007
Nitrogen oxide (NO_x)	0.028	no data
Propene (C_3H_6)	1.123	0.600
Sulphur oxide (SO_x)	0.048	no data
Toluene ($C_6H_5CH_3$)	0.637	0.500

The determination of the indicator photo-oxidant formation is given by

$$Photo-oxidant \quad formation = \sum_i POCP_i * m_i$$

m_i = mass of the substance released (in kg)
The unit of expression is *kg of ethylene (C_2H_4)* equivalent
In the adopted approach, only the characterization factors relative to the scenario with a high background concentration of NO_x are considered.

Abiotic Depletion Potential

Abiotic depletion indicators aim to capture the decreasing availability of non-renewable resources as a result of their extraction and underlying scarcity. Two types of indicators are considered:

- Abiotic Depletion Elements (addresses the extraction of scarce elements)
- Abiotic Depletion Energy/Fossil Fuels (addressing the use of fossil fuels as fuel or feedstock)

The Abiotic Depletion Potential (Elements) of resource *i* (ADPi) is given by the ratio between the quantity of resource extracted and the recoverable reserves of that resource, expressed in kg of the reference resource, Antimony, and the characterization factors for some selected resources are indicated in Table

Abiotic depletion potentials for some elements (in Sb eq./kg) (Guinée et al., 2002)

Resource	ADP element
Aluminium	1.09E-09
Cadmium	1.57E-01
Copper	1.37E-03
Iron	5.24E-08
Lead	6.34E-03

The determination of the indicator abiotic depletion (Elements) is given by

$$Abiotic \ Depletion = \sum_i ADP_i * m_i$$

m_i = quantity of resource extracted (in kg)
The unit of expression is *kg of antimony (the reference resource)*

Indicators describing input and output flows

Additional indicators are used for describing inputs and output flows. These indicators describe the use of renewable and non-renewable primary energy and water resources and they are calculated directly from input flows of the LCI.

Indicators describing resource use (EN15978, 2011)

Indicator	Unit
Use of renewable primary energy excluding energy resources used as raw material	MJ, net calorific value
Use of renewable primary energy resources used as raw material	MJ, net calorific value
Use of non-renewable primary energy excluding primary energy resources used as raw material	MJ, net calorific value
Use of non-renewable primary energy resources used as raw material	MJ, net calorific value
Use of secondary material	kg
Use of renewable secondary fuels	MJ
Use of non-renewable secondary fuels	MJ
Use of net fresh water	m^3

The indicators describing waste categories and waste categories and output flows are also based on the input flows of the LCI. They are indicated in the following tables

Indicators describing waste categories (EN15978, 2011)

Indicator	Unit
Hazardous waste disposed	kg
Non-hazardous waste disposed	kg
Radioactive waste disposed	kg

Indicators describing the output flows leaving the system (EN15978, 2011)

Indicator	Unit
Components for re-use	kg
Materials for recycling	kg
Materials for energy recovery (not being waste incineration)	kg
Exported energy	MJ for each energy carrier

2.3.5. Product Level (EN 15804, 2012)

An EPD is a particular type of LCA, conducted using a defined set of Product Category Rules (PCR). EPDs following the same PCR can be compared. EPDs show the quantified environmental impact data of products according to standard indicators. They are an effective way of communicating LCA results of products and allow direct access to the information. EPD's are verified, consistent and comparable data based on LCA. At the product level, EN 15804 standard defines the product category rules to develop Environmental Product Declarations (EPD) of construction products. EPDs are Type III environmental declarations, according to ISO 14025 (2006) and are often a good source of environmental data for a life cycle analysis. They also include relevant environmental aspects of products throughout their life cycle.

The scope of an LCA carried out at the material level may be the same as the one described for the building level. However, only the declaration of the product stage (modules A1 to A3) is mandatory in EN 15804, the declaration of the other life cycle stages is optional.

2.3.6. AMECO

AMECO 3 is a tool which assesses the environmental impacts of the bearing structures made of steel and concrete. AMECO 3 deals with either buildings or bridges made of steel and concrete. It takes into account 24 kinds of quantities (which have already been discussed) into the following groups:

- Environmental impacts
- Resources use,
- Other environmental information describing waste categories
- Other environmental information describing output flows

Each quantity is decomposed into the 4 modules already described previously. Ameco 3 allows the introduction of the use phase on the calculation of the environmental impact. It allows the estimation of energy needs for a variety of the building systems. Their calculation is based on several international norms such as ISO-13370, ISO-13789 and ISO-13790 as well as on European norm (EN 15316).

The calculation of impacts needs several quantities describing the structure, the way elements are transported to the site, and some information on how the elements involved will be used after the demolition of the structure. The calculation of the use phase needs several quantities defining the building.

Index	Data available	Abbreviation	Designation	Unit
Environmental impacts				
1	Yes	GWP	Global Warming Potential	*t CO_2 eq*
2	Yes	ODP	Ozone Depletion Potential	*t CFC eq*
3	Yes	AP	Acidification Potential	*t SO_2 eq*
4	Yes	EP	Eutrophication Potential	*t PO_4 eq*
5	Yes	POCP	Photochemical Ozone Creation Potential	*t Ethene eq*
6	Yes	ADP-e	Abiotic Depletion Potential – elements	*t Sb eq*
7	Yes	ADP-ff	Abiotic Depletion Potential – fossil fuels	*GJ NCV*
Resource use, secondary material and fuels				
8	No	RPE	Use of renewable primary energy excluding renewable primary energy resources used as raw materials	*GJ NCV*
9	No	RER	Use of renewable energy resources used as raw materials	*GJ NCV*
10	Yes	RPE-total	Total use of renewable primary energy (primary energy and primary energy resources used as raw materials)	*GJ NCV*
11	No	Non-RPE	Use of non renewable primary energy excluding non renewable primary energy resources used as raw materials	*GJ NCV*
12	No	Non-RER	Use of non renewable energy resources used as raw materials	*GJ NCV*
13	Yes	Non-RPE-total	Total use of non renewable primary energy (primary energy and primary energy resources used as raw materials)	*GJ NCV*
14	No	SM	Use of secondary material	*t*
15	No	RSF	Use of renewable secondary fuels	*GJ NCV*
16	No	Non-RSF	Use of non renewable secondary fuels	*GJ NCV*
17	Yes	NFW	Use of net fresh water	*$10^3 m^3$*
Other environmental information describing waste categories				
18	Yes	HWD	Hazardous waste disposed	*t*
19	Yes	Non-HWD	Non hazardous waste disposed	*t*
20	Yes	RWD	Radioactive waste disposed	*t*
Other environmental information describing output flows				
21	No	CR	Components for reuse	*t*
22	No	MR	Materials for recycling	*t*
23	No	MER	Materials for energy recovery	*t*
24	No	EE	Exported energy	*t*

2. Objectives

The objective of this study is to check the influence of fire protection methods on the sustainability of a building. An attempt is made to calculate the percentage influence of the fire protection while calculating the Life Cycle Assessment.

For the purpose of the study, a multi-storey building cum sports hall is taken into consideration. This model is chosen because it gives a wider range of results thus enabling us to understand the effects on different building models. The data used for the building model is close to a realistic structure, hence can be assumed to give more accurate results. The model is checked for influence in 3 different categories.

- Environmental Impact
- Impact on Resource Use
- Impact on Waste Categories

Beginning from a building model which was not designed for fire, different solutions to fire design are studied. These solutions are different combinations of

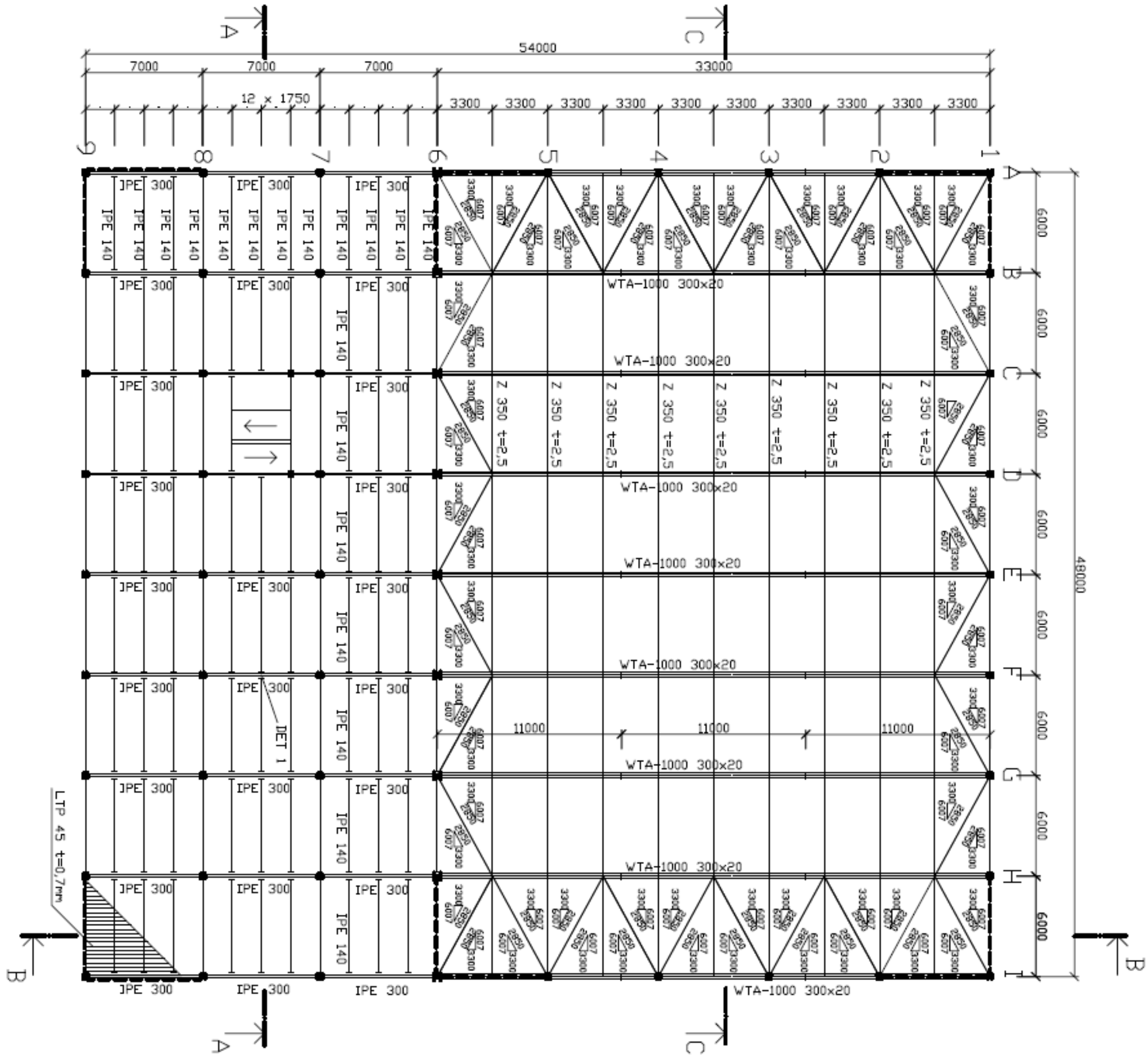
- Boarding
- Intumescent coating
- Spray painting
- Slim Floors
- Sprinkler Systems.

Then by the use of software and Environmental Product Declaration (EPD) of the fire protection materials, the LCA of the building is calculated and the impact of the fire protection methods is checked. Among these multiple solutions which will be checked, the solutions which give the best and worst performance in terms of its environmental performance are found and then compared. The results will give an idea on how important are these protection methods when sustainability of the building is concerned, the range of their influence and also how different fire protection methods perform under sustainability.

3. Case study

3.1. Building model

For this study, a multistoreybuilding attached with a sports hall was taken into consideration. The structure has been designed according to local standards and requirements in Prague and the preliminary design was obtained from the bachelor thesis of Mr Pavel Hrba–"Konstrukce sportovní haly Řepy". The design was also modified, where the original corrugated girder in the sports hall was replaced by a truss girder, details of which are given later. The schematics of the model is shown below



Ground plan (Hrba,P.,2013)

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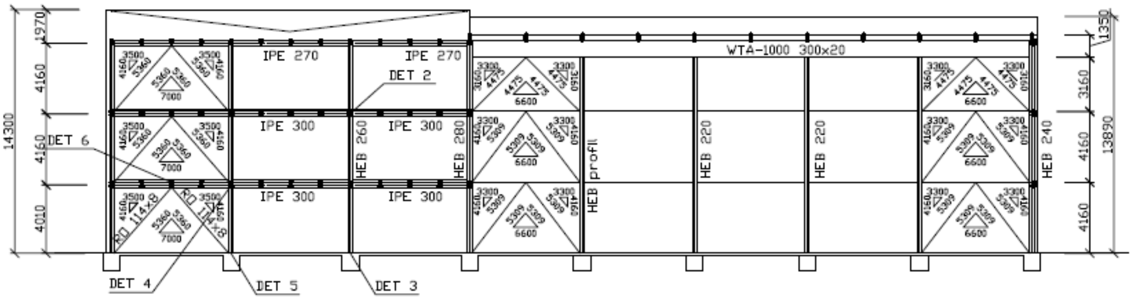
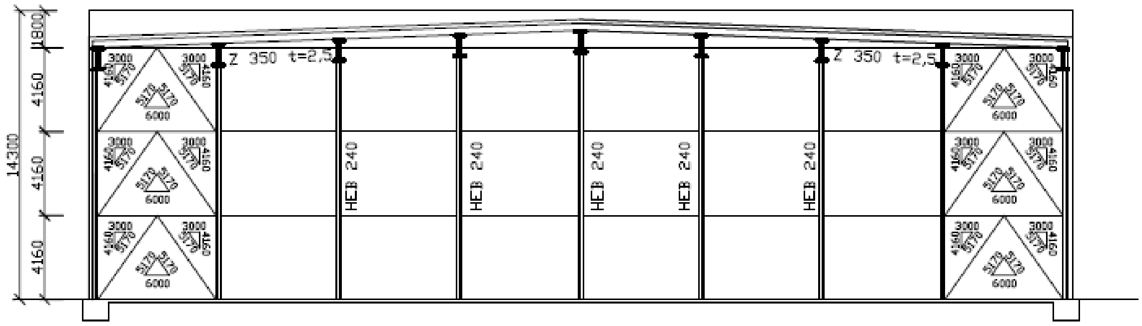
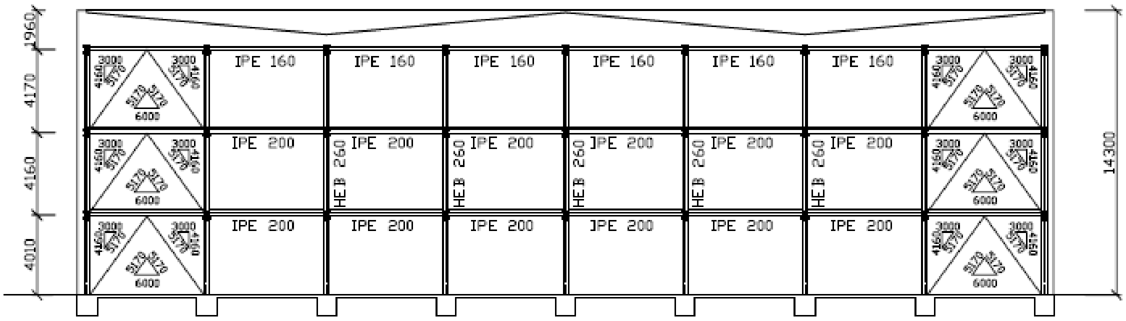


Elevation B-B (Hrba,P.,2013)



Elevation C-C (Hrba,P.,2013)



Elevation A-A (Hrba,P.,2013)

The structure is composed of two sections. A three storeyed office building and adjacent to it is a sports hall. The overall height of the building is 13m with individual floor height of 4.16m. The columns are H profiles whereas the beams are composite with IPE profiles and LTP 45 sheeting for slabs.

The details of the steel design is given in the table below

	Section
Multistorey Building	
Column	HEB 260
Primary Beam 3rd level	IPE 270
Primary Beam 2nd Level	IPE 300
Primary Beam 1st level	IPE 300
Secondary Beam 3rd Level	IPE 160
Secondary Beam 2nd Level	IPE 200

Secondary Beam 1st Level	IPE 200
Sports Hall	
Column (adjoining the office building)	HEB 280
Column (West end)	HEB 240
Column (North and south facade)	HEB 220
Main Beams	Truss Girder

Design of the truss girder:

The design of the trus girder followed the design procedures given in “Design handbook for Rautarukki structural hollow sections”. SAP2000 was used for the analysis.

Grade of Steel = S235

Depth of Girder = 2 m

Angle of Diagonal = 50^o

	Section
Upper Chord	SHS : 200 x 200 x 7.1
Lower Chord	SHS : 200 x 200 x 7.1
Diagonal	SHS : 120 x 120 x 4

3.2. Fire Resistance Check

The model is checked for fire resistance. The required resistance period for an office structure is 45 minutes and for the multipurpose sport hall, 60 minutes. The software Elefir-EN is used to check the steel components subjected to compression, tension and bending stresses. For the check of composite beams, a manual calculation is performed.

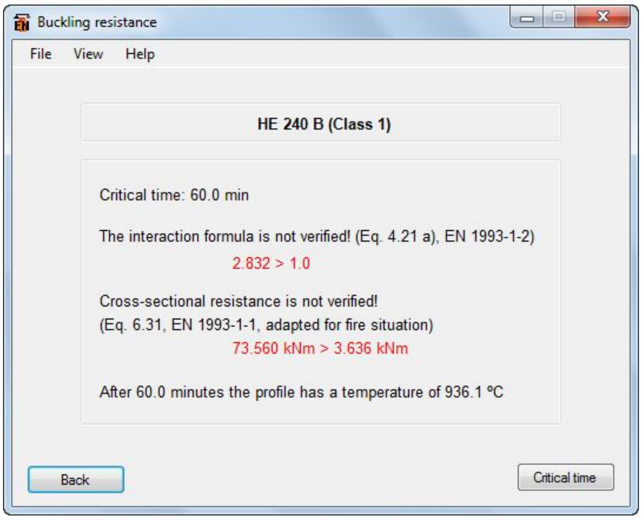
The calculation of loads at elevated temperature is defined in Chapter 2.3. Mechanical Loading. The values have been calculated and found accordingly.

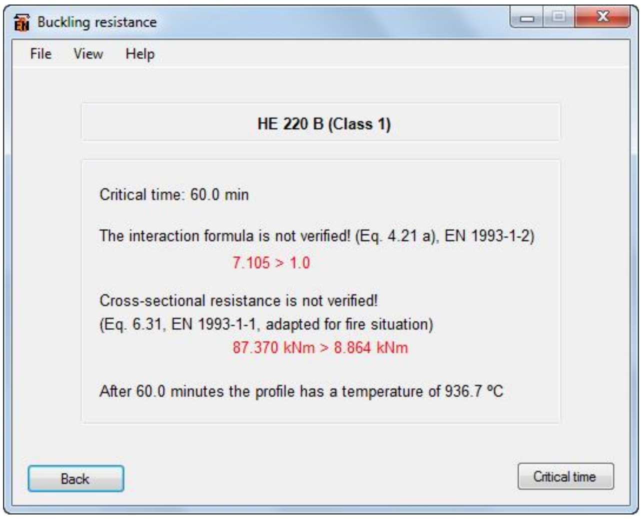
Column Check

Columns are checked in Elefir-EN for fire resistance.

Columns	Fire Resistance	L_{cry}	L_{crz}	Loads @ elevated temperature		Resistance@ elevated temperature	Critical temperature
		m	*m*	*kN*	*kNm*	*kN*	^oC
HEB 260	R45	4.16	4.16	632.23	-	163.287 kN	880.5
HEB 280	R60	4.16	4.16	425.15	16.12	163.457 kN	935.3
HEB 240	R60	13.3	4.16	99.11	73.56	Not satisfied	936.1
HEB 220	R60	12.4	4.16	26.10	87.37	Not satisfied	936.7

Hence the columns are not okay under fire condition and have to be designed.





Truss Girder check

The truss girder elements were also checked with Elefir-EN. The required fire resistance for the truss girder is R60

Section	L	Loads@ elevated temperature	Resistance@ elevated temperature	Critical Temperature
	m	*kN*	*kN*	^{o}C
Upper Chord 200 x 200 x 7.1	3.3	312.13 (compression)	50.219	940.4
Lower Chord 200 x 200 x 7.1	3.3	316.7 (tension)	66.134	940.4
Diagonal 120 x 120 x 4	2.6	90.88 (compression)	15.317	942.6
		93.5 (tension)	22.259	

Beam Check

The checks for beams - only the composite beams on the first and second floor level are checked for fire. It is assumed that the IPE 270 and IPE160 beams on the third level (not composite) require fire protection.

Secondary Beam	**IPE 200**		
Span	$L =$	6	m
	$f_y =$	235	N/mm^2
	$f_c =$	25	N/mm^2
	$\gamma_{mfi} =$	1	
Effective width	$b_{eff} =$	1500	mm
Depth of beam	$d =$	200	mm
Depth of slab	$d_c =$	110	mm
	$b_f =$	100	mm
	$t_f =$	8.5	mm
	$t_w =$	5.6	mm
	$h_w =$	183	mm

Lower Flange

Section factor	$A_m/V =$	248.7	m^{-1}
Steel temperature after 45 mins	$\theta_{a,1} =$	897.9	C

Obtained by iteration from Table for Temperature of unprotected steel in °C exposed to ISO 834 fire curve for different values of $k_{sh}\frac{A_m}{V}$

Reduction factor for yield strength	$k_{y\,\theta} =$	0.061	

Obtained by iteration from Table for Reduction factors for stress-strain relationship of carbon steel at elevated temperatures

Reduced design strength	$f_{y\theta 1} =$	14.34	N/mm^2

Web

Section factor	$A_m/V =$	357.14	m^{-1}	
Steel temperature after 45 mins	$\theta_{a,1} =$	899.57	^oC	*From Table*
Reduction factor for yield strength	$k_{y\,\theta} =$	0.060		*From Table*
Reduced design strength	$f_{y\theta 1} =$	14.15	N/mm^2	

Upper Flange

Section factor	$A_m/V =$	131.06	m^{-1}	
Steel temperature after 45 mins	$\theta_{a,1} =$	891.5	^oC	*From Table*
Reduction factor for yield strength	$k_{y\,\theta} =$	0.064		*From Table*
Reduced design strength	$f_{y\theta 1} =$	15.10	N/mm^2	

Tension force in the steel part	$T =$	39.52	kN
Thickness of compressed part in concrete	$h_u =$	1.054	mm
Bending moment resistance	$M_{fiRd} =$	**8.26**	kNm

Primary Beam	**IPE 300**		
Span	$L =$	7	m
	$f_y =$	235	N/mm^2
	$f_c =$	25	N/mm^2
	$\gamma_{mfi} =$	1	
Effective width	$b_{eff} =$	1750	mm

Depth of beam	d =	300	*mm*	
Depth of slab	d_c =	110	*mm*	
	b_f =	150	*mm*	
	t_f =	10.7	*mm*	
	t_w =	7.1	*mm*	
	h_w =	278.6	*mm*	
	Lower Flange			
Section factor	A_m/V =	195.82	m^{-1}	
Steel temperature after 45 mins	$\theta_{a,1}$ =	896.6	*C*	*From Table*
Reduction factor for yield strength	$k_{y\,\theta}$ =	0.061		*From Table*
Reduced design strength	$f_{y\theta 1}$ =	14.49	N/mm^2	
	Web			
Section factor	A_m/V =	281.69	m^{-1}	
Steel temperature after 45 mins	$\theta_{a,1}$ =	898.63	^oC	*From Table*
Reduction factor for yield strength	$k_{y\,\theta}$ =	0.060		*From Table*
Reduced design strength	$f_{y\theta 1}$ =	14.26	N/mm^2	
	Upper Flange			
Section factor	A_m/V =	102.37	m^{-1}	
Steel temperature after 45 mins	$\theta_{a,1}$ =	889.19	*C*	*From Table*
Reduction factor for yield strength	$k_{y\,\theta}$ =	0.065		*From Table*
Reduced design strength	$f_{y\theta 1}$ =	15.37	N/mm^2	
Tension force in the steel part	T =	76.14	*kN*	
Thickness of compressed part in concrete	h_u =	1.74	*mm*	
Bending moment resistance	M_{fiRd} =	**19.663**	***kNm***	

	Loads @ elevated temperature	Resistance @ elevated temperature	Result
	M_{ed} (kNm)	M_{rd} (kNm)	
IPE 200	44.1	8.26	Not safe
IPE 300	105.96	19.663	Not safe

Thus we see that the beams are also not safe for fire design

3.3. Fire protection

Fire protection for the following study are taken in the following ways

Boarding

Product name: Promatect H

Description: It is a non combustible matrix engineered mineral board reinforced with selected fibres and fillers. It is resistant to the effects of moisture and will not physically deteriorate when used in damp conditions or humid conditions. This product is suitable where higher impact resistance is needed. Promat products have been tested to a variety of standards including BS476: Part 21

Protection type: Box protection

Hp/A = Box section factor

Fire protection time: R60 was considered for all members and not R45 as there are no tables available for R45. The thickness of the board is estimated from the standard tables from Promat

HE 220

Hp	=	880	*mm*
A	=	9100	mm^2
Hp/A	=	96.7	m^{-1}
Fire Resistance	=	60	*min*
Board thickness	=	15	*mm*

HE 240

Hp	=	960	*mm*
A	=	10600	mm^2
Hp/A	=	90.57	m^{-1}
Fire Resistance	=	60	*min*
Board thickness	=	15	*mm*

HE 260

Hp	=	1040	*mm*
A	=	11840	mm^2
Hp/A	=	87.84	m^{-1}
Fire Resistance	=	60	*min*
Board thickness	=	15	*mm*

HE 280

Hp	=	1120	*mm*
A	=	13140	mm^2
Hp/A	=	85.24	m^{-1}
Fire Resistance	=	60	*min*
Board thickness	=	15	*mm*

IPE 160

Hp	=	500	*mm*
A	=	2850	mm^2
Hp/A	=	175.44	m^{-1}

Fire Resistance	=	60	*min*
Board thickness	=	15	*mm*

IPE 270

Hp	=	750	*mm*
A	=	5380	mm^2
Hp/A	=	139.40	m^{-1}
Fire Resistance	=	60	*min*
Board thickness	=	12	*mm*

Intumescent Paints

Product Name: CAFCO Sprayfilm WB3 from Promat

Description: It is a water based intumascent coating consisting of polyvinyl acetate resins and filters for the fire protection of structural steel. It can be applied directly to steel profiles as contour protection. In the case of fire, a chemical reaction causes the paint to expand and form an insulating layer. The product has tested in accordance Bs 476: Part 21

The thickness of the fire protection for a given period of fire resistance depends on the Hp/A ratio of the steel section.

Protection type: Profile

Hp/A = Profile section factor

R60 was considered for all members and not R45 as there are no tables available for R45. The thickness of the coating is estimated from the standard tables from Promat

HE 220

Hp	=	1270	*mm*
A	=	9100	mm^2
Hp/A	=	139.56	m^{-1}
Fire Resistance	=	60	*min*
Coating thickness	=	0.8	*mm*

HE 240

Hp	=	1384	*mm*
A	=	10600	mm^2
Hp/A	=	130.57	m^{-1}
Fire Resistance	=	60	*min*
Coating thickness	=	0.75	*mm*

HE 260

Hp	=	1499	*mm*
A	=	11840	mm^2
Hp/A	=	126.60	m^{-1}

Fire Resistance	=	60	*min*
Coating thickness	=	0.71	*mm*

HE 280

Hp	=	1618	*mm*
A	=	13140	mm^2
Hp/A	=	123.14	m^{-1}
Fire Resistance	=	60	*min*
Coating thickness	=	0.66	*mm*

IPE 200

Hp	=	668	*mm*
A	=	2850	mm^2
Hp/A	=	234.39	m^{-1}
Fire Resistance	=	60	*min*
Coating thickness	=	0.93	*mm*

IPE 300

Hp	=	1010	*mm*
A	=	5380	mm^2
Hp/A	=	187.73	m^{-1}
Fire Resistance	=	60	*min*
Coating thickness	=	0.7	*mm*

IPE 270

Hp	=	1041	*mm*
A	=	4590	mm^2
Hp/A	=	226.80	m^{-1}
Fire Resistance	=	60	*min*
Coating thickness	=	1.13	*mm*

IPE 160

Hp	=	623	*mm*
A	=	2010	mm^2
Hp/A	=	309.95	m^{-1}
Fire Resistance	=	60	*min*
Coating thickness	=	1.49	*mm*

SHS 200 x 200 x 7.1

Hp	=	769	*mm*
A	=	5305	mm^2

Hp/A	=	144.96	m^{-1}
Fire Resistance	=	60	*min*
Coating thickness	=	1.08	*mm*

SHS 120 x 120 x 4

Hp	=	466	*mm*
A	=	1815	mm^2
Hp/A	=	256.75	m^{-1}
Fire Resistance	=	60	*min*
Coating thickness	=	1.64	*mm*

Spray

Product Name: CAFCO 300 from Promat

Description: Gypsum based vermiculite spray. It has been tested in accordance with BS476.

Protection type: Profile protection

Thickness of the spray depends on the profile Section factor, Hp/A and the critical temperature of the members. The thickness was calculated from the standard tables provided in the product catalogue.

Protection type: Profile

Hp/A = Profile section factor

R60 was considered for all members and not R45 as there are no tables available for R45. The thickness of the spray is estimated from the standard tables from the Yellow Book by Association for Specialist Fire Protection

HE 220

Hp	=	1270	*mm*
A	=	9100	mm^2
Hp/A	=	139.56	m^{-1}
Fire Resistance	=	60	*min*
Spray thickness	=	12	*mm*

HE 240

Hp	=	1384	*mm*
A	=	10600	mm^2
Hp/A	=	130.57	m^{-1}
Fire Resistance	=	60	*min*
Spray thickness	=	12	*mm*

HE 260

Hp	=	1499	*mm*
A	=	11840	mm^2
Hp/A	=	126.60	m^{-1}
Fire Resistance	=	60	*min*
Spray thickness	=	12	*mm*

HE 280

Hp	=	1618	*mm*
A	=	13140	mm^2
Hp/A	=	123.14	m^{-1}
Fire Resistance	=	60	*min*
Spray thickness	=	12	*mm*

IPE 200

Hp	=	668	*mm*
A	=	2850	mm^2
Hp/A	=	234.39	m^{-1}
Fire Resistance	=	60	*min*
Spray thickness	=	14	*mm*

IPE 300

Hp	=	1010	*mm*
A	=	5380	mm^2
Hp/A	=	187.73	m^{-1}
Fire Resistance	=	60	*min*
Spray thickness	=	13	*mm*

IPE 270

Hp	=	1041	*mm*
A	=	4590	mm^2
Hp/A	=	226.80	m^{-1}
Fire Resistance	=	60	*min*
Spray thickness	=	14	*mm*

IPE 160

Hp	=	623	*mm*
A	=	2010	mm^2
Hp/A	=	309.95	m^{-1}

Fire Resistance	=	60	*min*
Spray thickness	=	15	*mm*

SHS 200 x 200 x 7.1

Hp	=	*769*	*mm*
A	=	*5305*	mm^2
Hp/A	=	*144.96*	m^{-1}
Fire Resistance	=	*60*	*min*
Spray thickness	=	*12*	*mm*

SHS 120 x 120 x 4

Hp	=	*466*	*mm*
A	=	*1815*	mm^2
Hp/A	=	*256.75*	m^{-1}
Fire Resistance	=	*60*	*min*
Spray thickness	=	*14*	*mm*

Slim Flooring

Product: Slimdek

Description: Slimdek is an engineered flooring solution. It offers a cost-effective, minimal depth floor for use in multi-storey steel-framed buildings.The grids can be upto 9m x 9m. It is formed with ComFlor 225 deep decking spanning between Asymmetric Slimflor Beams (ASBs) and/or Rectangular Hollow Slimflor Beams (RHSFBs). The slimfloor is designed for R60 and the details of the elements are obtained from the manufacturer manual.

Beam = 280ASB (FE) 100

Depth = 290 mm

Bar diameter = 16mm

Sheeting = ComFlor 225

Normal weight concrete with 4.0 kN/m^2 LL

Sprinklers for Truss Girder

From the table below, the density of water can be chosen for the sprinkler system as a function of the critical temperature.

Final Temperatures of structures located outside direct water impingement as a function of water density for different moments in time (Jukka Vaari)

TRUSSES			
Density (mm/min)	60 min	90 min	120 min
5.0	443	501	554
7.5	366	416	454
10.0	359	401	432
12.5	299	336	369

Since the critical temperature of the truss girder is higher than 443 oC for R60, 5.0 mm/min is chosen for the sprinkler water density.

4. Sensitivity Study

In this chapter the comparison of the different fire protection methods are made in order to obtain the behaviour of these methods in sustainability of the building. For this purpose, the environmental product declarations (EPD) of the fire protection materials are used. In some cases, as the EPD of specific product is not available, a similar product but of a different brand has been used under the assumption that they will have similar impact on the sustainability. The details are given in the following paragraphs.

Among the many combinations for fire design, the best and the worst case in terms of its sustainable performance is chosen and then compared to find the range of influence and overall sustainability.

To find the best and the worst case, comparison is done in the structure level only since the fire protection does not influence the use stage of the building. For the structure, the software AMECO is used to get the values of impact. In order to obtain the influence of fire protection in the structure level as well as the building level, two different analyses has been run in the software - One with structure only and the other, including the envelope. Standard materials have been included for the envelope properties and are given below.

The first case is the case study where no fire protection has been provided. Later different combinations of fire protection are made and compared with the case study. This will give us the influence of the fire protection on the LCA of the building. The comparison is made for the multi-storey building, sports hall and the entire structure as a whole.

Description of the different cases for fire protection

	Type of fire protection used		
Case	For Columns	For Beams	For Truss Girder
Case Study	No Protection	No Protection	No Protection
Case 1	Boarding	Boarding	Spray
Case 2	Intumescent	Boarding	Intumescent
Case 3	Intumescent	Intumescent	Intumescent
Case 4	Spray	Spray	Spray
Case 5	Boarding	Slim Floor	Spray
Case 6	Boarding	Slim Floor	Intumescent
Case 7	Intumescent	Slim Floor	Intumescent
Case 8	Spray	Slim Floor	Spray
Case 9	Intumescent	Spray	Spray
Case10	Boarding	Spray	Spray

Calculating amount of fire protection material in each case

	Boarding (m^2)			Intumescent (kg)			Spray (kg)		
	Multi storey	Sports Hall	Full Model	Multi storey	Sports Hall	Full Model	Multi storey	Sports Hall	Full Model
Case Study	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Case 1	1834.9	321.5	2030.6	0.0	0.0	0.0	0.0	974.7	974.7
Case 2	1834.9	321.5	2030.6	0.0	123.8	123.8	0.0	0.0	0.0
Case 3	0.0	0.0	0.0	249.8	176.4	408.2	0.0	0.0	0.0
Case 4	0.0	0.0	0.0	0.0	0.0	0.0	2668.1	1614.4	4040.3
Case 5	472.3	321.5	668.0	0.0	0.0	0.0	0.0	974.7	974.7
Case 6	472.3	321.5	668.0	0.0	123.8	123.8	0.0	0.0	0.0
Case 7	0.0	0.0	0.0	35.7	176.4	194.1	0.0	0.0	0.0
Case 8	0.0	0.0	0.0	0.0	0.0	0.0	464.3	1614.4	1836.4
Case 9	0.0	0.0	0.0	35.7	52.6	70.3	2203.9	974.7	3178.5
Case 10	472.3	321.5	668.0	0.0	0.0	0.0	2203.9	974.7	3178.5

4.1. AMECO - Input

Input values for AMECO software for different cases

	Multi-Storey (Case Study)	Sport Hall	Multi-Storey (Slim Floor)
Building			
North - South façade Length *(m)*	21	33	21
East West façade Length *(m)*	48	48	48
Floor height *(m)*	4.16	12.48	4.16
Floor height under ceiling *(m)*	4.16	12.48	4.16
Structure only	No		
No of intermediate floors	2	0	2
Building type	Office	Industrial	Office
Country	Czech Republic		
Location	Prague		
Envelope			
Façade area –North	30%	15%	30%
Façade area – East	0%	30%	0%
Façade area – South	30%	15%	30%
Façade area – West	30%	0%	30%
Façade			
Wall type	Light steel Panel Wall (Rock wool) panel Wall		
Opening type	Double Glazing		
Shading Device type and colour	No shading devive		
Shutter Type	No shutter		

Base Floor			
U Value *W/(m².K)*	0.599		
Base Floor type	Slab on ground floor		
Thickness of concrete *(m)*	0.2		
Mass of Reinforcing steel *(t)*	0		
internal heat capacity -ground floor *J/(m².K)*	50000		
internal heat capacity -intermediate floor	50000		
Internal heat capacity of internal walls *J/(m².K)*	20000		
Roof			
Roof type	Roof type 2	Waterproof membrane	Roof type 2
U-Value for the roof (flat part) *W/(m².K)*	0.373	0.31	0.373
Occupancy			
Heating set-point temperature *(°C)*	20		
Cooling set-point temperature *(°C)*	26		
Air flow rate (heating mode) *(ac/h)*	0.6		
Air flow rate (cooling mode) *(ac/h)*	1		
Systems			
Heating	Split (heating)		
Cooling	Split (cooling)		
Heat recovery	Yes		
Percentage	80		
Efficiency	0.6		
DHW	Electric Boiler		
Structure			
Beams (hot rolled profiles) *(t)*	60.6	3.35	54.6
Columns (Hot rolled Profiles) *(t)*	42.6	28.1	42.6
Studs *(t)*	0.0	0.0	0.0
Bolts *(t)*	0.0	0.0	0.0
Plate Connections *(t)*	0.0	0.0	0.0
Floors			
Steel Elements			
Type of slab	Composite Slab		
Steel deck	LTP 45	-	ComFlor225
thickness of the deck *(mm)*	0.7	-	1.25
Mass of sheeting per m² of floor *(kg/m²)*	7.6	-	17.3
Mass of sheeting for the building *(t)*	15.3	-	34.9
Minimum depth of floor *(mm)*	43	-	225
Concrete elements			
Total depth of the floor *(mm)*	110.0	-	290

Concrete type	In-situ/Poured		
Concrete grade	C30/37		
Total mass of the floor concrete *(t)*	913.489	747.6	1051
Steel reinforcement *(t)*	2.53	747.6	2.65
Transport			
Steel Elements			
Total steel transported *(t)*	121.1	31.45	134.8
Values for the transport impacts	Average		
Concrete Elements			
Total concrete transported *(t)*	913.5	747.6	1051
Concrete produced on site *(t)*	913.5	747.6	1051
Distance by mixer trucks *(km)*	30.0	30.0	30.0
Prefabricated concrete *(t)*	0.0	0.0	0.0
Distance by regular trucks *(km)*	0.0	0.0	0.0

4.2. Fire protection

As the Environmental Product declaration of the designed fire protection materials was not available for evaluation, the LCA values from similar products have been used for this study. The impact values for these materials are available in tables in Annex A of this report. The details of the materials are given below.

Boarding

Product :	15 mm Glasroc F FIRECASE
Manufacturer :	BPB United Kingdom Limited trading as British Gypsum
Codes Followed :	EN 15804 and ISO 14025
EPD registration number :	S-P-00471
Declared unit :	1m^2 of 15mm thick Glasroc F FIRECASE
Reference service life :	60 years

Intumescent

Product :	HENSOTHERM® 2 P INTERIOR white
Manufacturer :	Rudolf Hensel GmbH
Codes Followed :	EN 15804
EPD registration number :	EPD-RHG-20140058-IAA1-DE
Declared unit :	1 kg
Reference service life :	25 years

Spray

Product :	Gypsum based construction and industrial plasters
Manufacturer :	Dalsan Gypsum Industry and Trade Inc.
Codes Followed :	EN 15804

EPD registration number : EPD-DGI-20130058-CBC1-EN
Declared unit : 1 kg
Reference service life : Long life – Assumed to be as much as the service life of building

Sprinklers

Environmental product declarations for sprinklers are not available yet. Hence they will be a part of this study

4.3. Environmental Impact

In this section, the environmental impact is studied and compared. The Environmental categories are

GWP Global Warming Potential
ODP Ozone Depletion Potential
AP Acidification Potential
EP Eutrophication Potential
POCP Photochemical Ozone creation potential
ADPE Abiotic depletion potential –Elements
ADPF Abiotic depletion potential – Fossil Fuels

The LCA for different cases are calculated when only the frame was assessed. The envelope was not considered as it has the same effect in every case. The structure considered was the complete building including the multi-storey and the sports hall.

Total Impact = Impact of Structural frame + Impact of Fire protection

Structural Frame - Full Model	Environmental Impact						
	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Case Study	211.59	0.000008	0.57	0.07	0.07	-0.00044	2031.76
Case 1	226.55	0.000010	0.61	0.08	0.07	0.00046	2250.25
Case 2	227.69	0.000010	0.62	0.08	0.07	-0.00044	2274.71
Case 3	215.70	0.000008	0.59	0.08	0.07	-0.00043	2118.70
Case 4	212.01	0.000008	0.57	0.07	0.07	0.00328	2039.66
Case 5	253.48	0.000010	0.68	0.09	0.08	0.00086	2398.94
Case 6	254.62	0.000010	0.69	0.09	0.08	-0.00004	2423.41
Case 7	250.44	0.000010	0.68	0.09	0.08	-0.00004	2367.14
Case 8	248.68	0.000009	0.67	0.08	0.08	0.00165	2329.38
Case 9	212.63	0.000008	0.57	0.07	0.07	0.00249	2052.95
Case 10	216.81	0.000008	0.58	0.07	0.07	0.00249	2109.22

The percentage increase in the environmental impact after including the fire protection is calculated

Percentage Increase in Environmental Impact							
	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	%	%	%	%	%	%	%
Case 1	7.07	21.95	7.84	11.05	6.43	-203.93	10.75
Case 2	7.61	22.76	8.90	14.82	7.15	-0.89	11.96
Case 3	1.94	3.18	3.67	13.03	2.78	-1.86	4.28
Case 4	0.20	0.64	0.21	0.74	0.54	-843.99	0.39
Case 5	19.80	28.11	19.92	24.30	18.23	-294.34	18.07
Case 6	20.34	28.92	20.98	28.08	18.94	-91.30	19.28
Case 7	18.36	22.30	19.06	26.75	17.35	-91.52	16.51
Case 8	17.53	21.08	17.41	20.89	16.27	-474.25	14.65
Case 9	0.49	1.05	0.80	2.83	0.90	-664.30	1.04
Case 10	2.47	7.67	2.73	4.16	2.50	-664.09	3.81

- Case 4, in which only spray protection is used has the least environmental impact. But since it is not common to use Spray on visible parts of the building due to the aesthetics, Case 9 where the columns are protected with intumescent paint is chosen as the best type of protection for the given model
- Case 6 is the worst in case of environmental impact and will be compared with the best scenario later.

4.3.1. Best Case: Case 9

Case	For Columns	For Beams	For Truss Girder
Case 9	Intumescent	Spray	Spray

Percentage influence of components of the Multi-storey on Environmental Impact

		Best Case - Environmental Impact						
Multi-storey – With envelope		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		%	%	%	%	%	%	%
Modules: Total A to D	Envelope	97.73	64.38	98.70	97.05	97.50	44.02	98.74
	Structural Frame	2.26	35.37	1.30	2.90	2.49	-10.27	1.25
	Fire protection	0.007	0.248	0.006	0.049	0.015	66.254	0.008

		Best Case - Environmental Impact						
Multi-storey – Structural Frame only		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		%	%	%	%	%	%	%
Modules: Total A to D	Structural Frame	99.69	99.30	99.52	98.34	99.40	-18.35	99.34
	Fire protection	0.309	0.696	0.484	1.661	0.599	118.354	0.658

Percentage influence of components of the Sport Hall on Environmental Impact

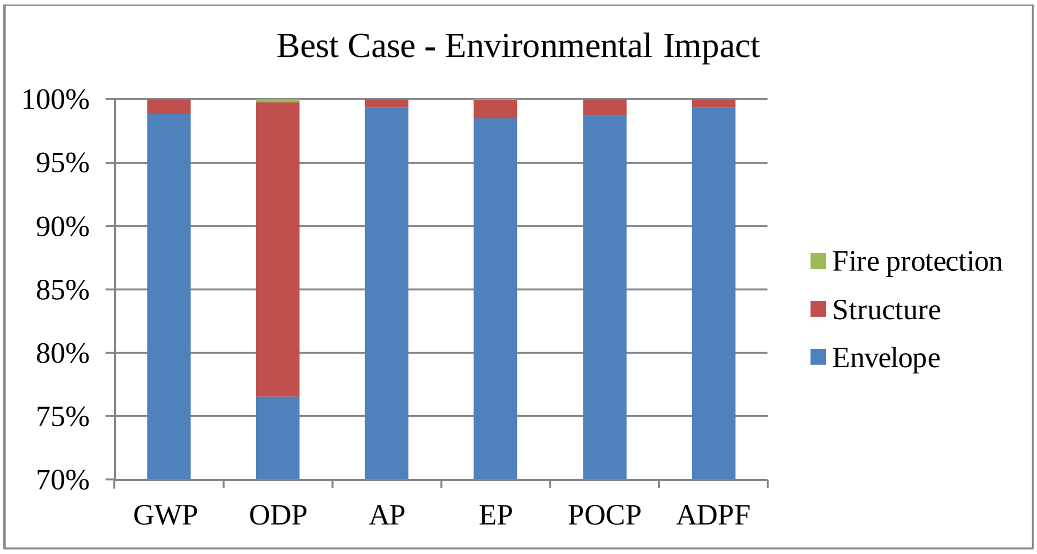
	Best Case - Environmental Impact

Sport Hall– With envelope		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		%	%	%	%	%	%	%
Modules: Total A to D	Envelope	99.64	90.33	99.78	99.57	99.54	84.71	99.77
	Structural	0.35	9.36	0.22	0.37	0.45	-4.39	0.22
	Fire protection	0.007	0.303	0.007	0.052	0.012	19.673	0.008

		Best Case - Environmental Impact						
Sport Hall – Structural Frame only		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		%	%	%	%	%	%	%
Modules: Total A to D	Structural Frame	98.16	96.86	97.03	87.85	97.38	-28.70	96.59
	Fire protection	1.838	3.136	2.974	12.149	2.624	128.700	3.406

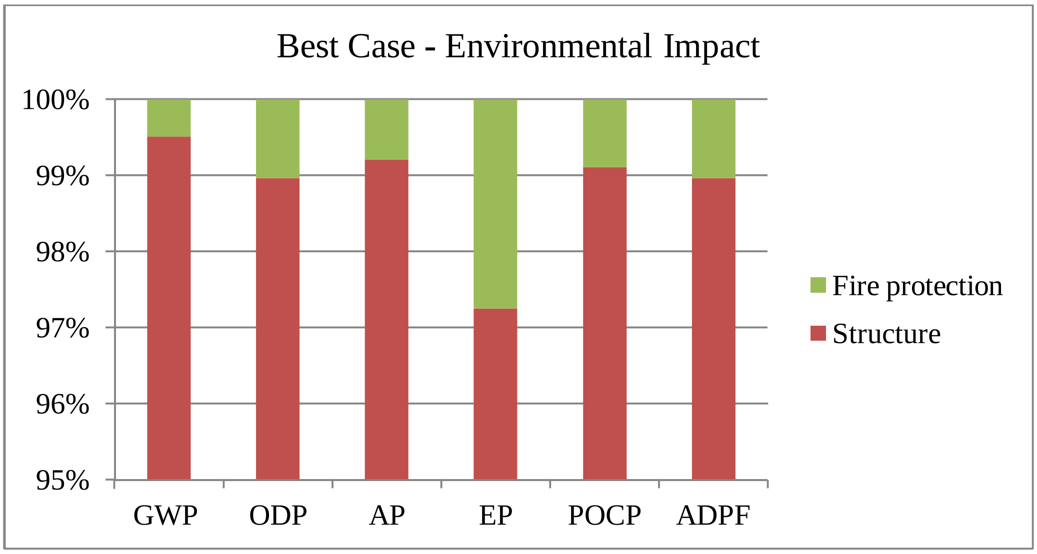
Percentage influence of components of the Full Model on Environmental Impact

		Best Case - Environmental Impact						
Full Model – With Envelope		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		%	%	%	%	%	%	%
Modules: Total A to D	Envelope	98.82	76.55	99.32	98.47	98.67	67.72	99.34
	Structural	1.18	23.20	0.68	1.49	1.32	-5.72	0.65
	Fire protection	0.006	0.243	0.005	0.042	0.012	38.002	0.007



	Best Case - Environmental Impact						
Full Model – Structural	GWP	ODP	AP	EP	POCP	ADPE	ADPF

Frame Only		%	%	%	%	%	%	%
Modules: Total A to D	Structural Frame	99.51	98.96	99.21	97.25	99.11	-17.72	98.97
	Fire protection	0.489	1.037	0.790	2.751	0.892	117.721	1.032



- Here we can notice that the influence of the fire protection on the environmental impact of each category is very small and most of the influence is from the envelope of the building, which means that the use stage (module B) of the building has the most influence.
- The effect of fire protection is more evident when only the structural frame is considered

4.3.2. Worst Case – Case 6

Case	For Columns	For Beams	For Truss Girder
Case 6	Boarding	Slim Floor	Intumescent

Percentage influence of components of the Multi-storey on Environmental Impact

		Worst Case - Environmental Impact						
Multi-storey – With envelope		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		%	%	%	%	%	%	%
Modules: Total A to D	Envelope	97.28	58.52	98.43	96.39	97.04	94.05	98.52
	Structural	2.68	39.65	1.54	3.53	2.92	5.93	1.45
	Fire protection	0.041	1.829	0.026	0.080	0.041	0.024	0.035

	Worst Case - Environmental Impact						
Multi-storey – Structural	GWP	ODP	AP	EP	POCP	ADPE	ADPF

Frame only		%	%	%	%	%	%	%
Modules: Total A to D	Structural Frame	98.50	95.59	98.33	97.79	98.62	99.60	97.65
	Fire protection	1.498	4.409	1.671	2.208	1.384	0.395	2.351

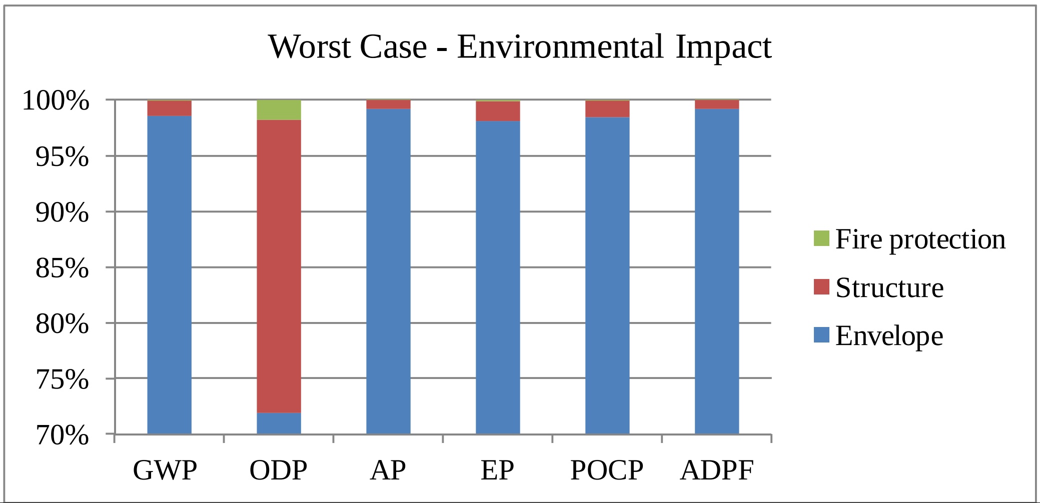
Percentage influence of components of the Sport Hall on Environmental Impact

		Worst Case - Environmental Impact						
Sport Hall– With envelope		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		%	%	%	%	%	%	%
Modules: Total A to D	Envelope	99.61	88.50	99.75	99.47	99.51	105.38	99.74
	Structural Frame	0.35	9.17	0.22	0.37	0.45	-5.46	0.22
	Fire protection	0.038	2.329	0.030	0.158	0.046	0.074	0.036

		Worst Case - Environmental Impact						
Sport Hall – Structural Frame only		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		%	%	%	%	%	%	%
Modules: Total A to D	Structural Frame	90.35	79.75	87.92	70.31	90.76	101.38	85.97
	Fire protection	9.646	20.253	12.083	29.690	9.242	-1.376	14.030

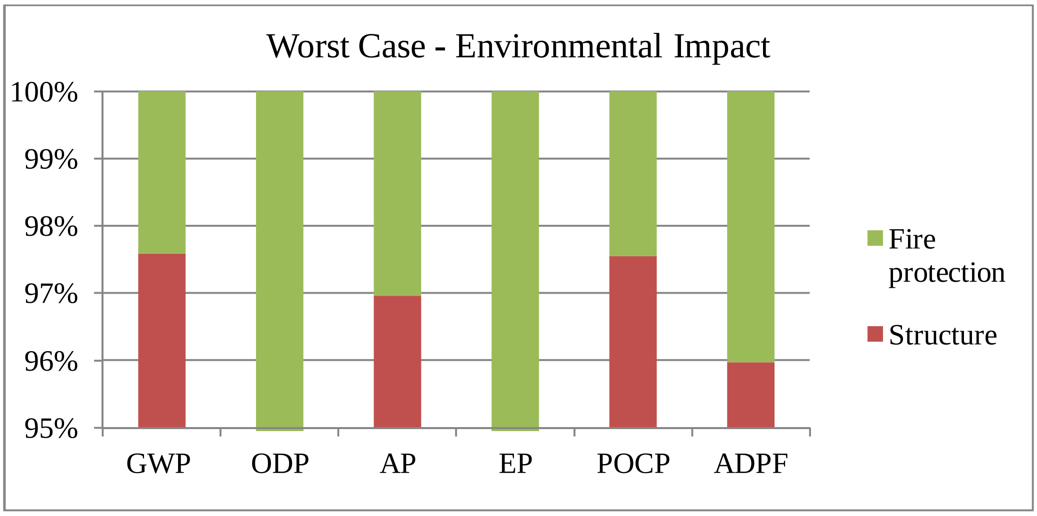
Percentage influence of components of the full model on Environmental Impact

		Worst Case - Environmental Impact						
Full Model – With Envelope		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		%	%	%	%	%	%	%
Modules: Total A to D	Envelope	98.59	71.90	99.18	98.10	98.44	100.74	99.22
	Structural	1.38	26.32	0.79	1.78	1.53	-0.80	0.75
	Fire protection	0.034	1.773	0.025	0.111	0.038	0.057	0.031



	Worst Case - Environmental Impact						
Full Model – Structural	GWP	ODP	AP	EP	POCP	ADPE	ADPF

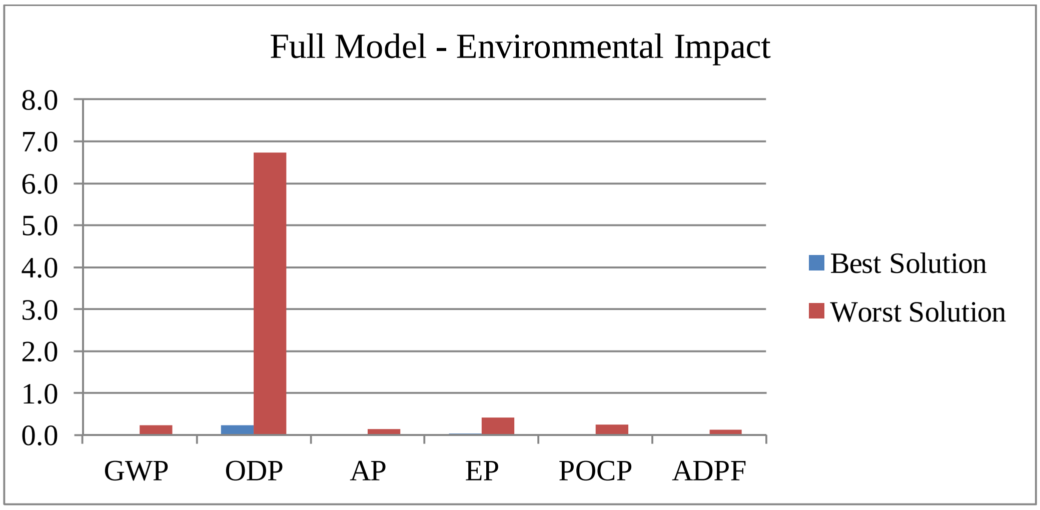
Frame Only		%	%	%	%	%	%	%
Modules: Total A to D	Structural Frame	97.59	93.69	96.96	94.12	97.55	107.74	95.97
	Fire protection	2.409	6.309	3.037	5.878	2.452	-7.741	4.028



4.3.3. Comparison between the Best and Worst solutions

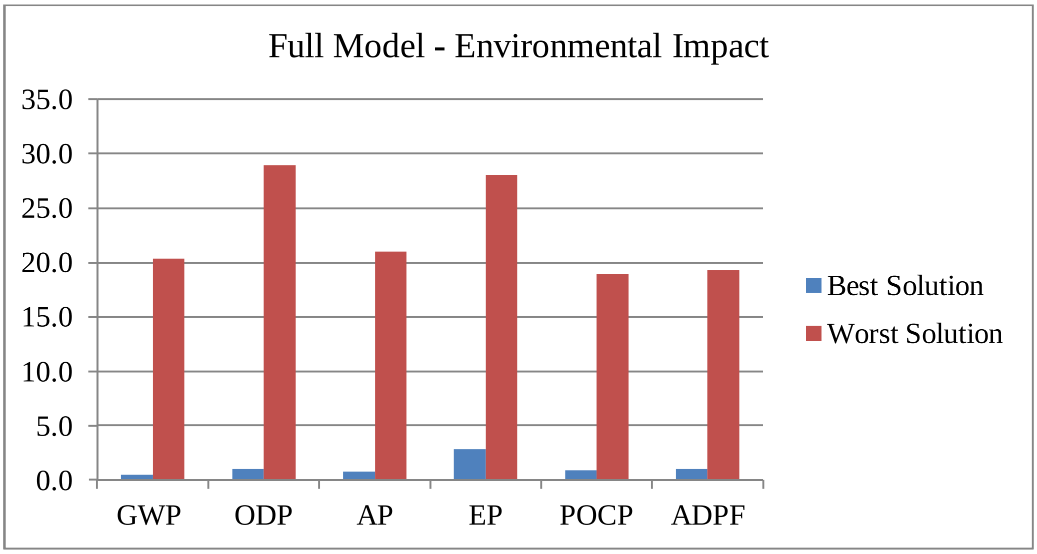
The increase in the percentage of environmental impact under each category for the full model is checked both at the structural frame level and when including the envelope with use phase.

Percentage influence of fire protection when the full model is considered						
	GWP	ODP	AP	EP	POCP	ADPF
	%	%	%	%	%	%
Best Solution	0.006	0.244	0.005	0.042	0.012	0.007
Worst Solution	0.239	6.727	0.142	0.417	0.250	0.126



Percentage influence of fire protection when the only the structural frame is considered						
	GWP	ODP	AP	EP	POCP	ADPF

	%	%	%	%	%	%
Best Solution	0.006	0.244	0.005	0.042	0.012	0.007
Worst Solution	0.239	6.727	0.142	0.417	0.250	0.126



4.4. Resource Use

Similar calculations like that for Environmental impact were carried out for the impact on resource use. The impact categories are

RPE	Use of renewable primary energy excluding renewable primary energy resources used as raw materials
RER	Use of renewable energy resources used as raw materials
RPE-total	Total use of renewable primary energy (primary energy and primary energy resources used as raw materials)
Non-RPE	Use of non renewable primary energy excluding non renewable primary energy resources used as raw materials
Non-RER	Use of non renewable energy resources used as raw materials
Non-RPE-total	Total use of non renewable primary energy (primary energy and primary energy resources used as raw materials)
SM	Use of secondary material
RSF	Use of renewable secondary fuels
Non-RSF	Use of non renewable secondary fuels
NFW	Use of net fresh water

Total Impact = Impact of Structural frame + Impact of Fire protection

	Resource Use

Structural Frame - Full Model	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	GJ NCV	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*1000m³*
Case	116.8	0.0	116.8	2318.3	0.0	2318.3	535.9	15.1	158.	31.8
Case 1	162.0	0.0	162.0	2564.4	0.0	2564.4	536.0	15.1	158.	31.8
Case 2	162.4	0.0	162.4	2583.2	6.0	2589.2	536.0	15.1	158.	31.8
Case 3	118.5	0.0	118.5	2386.6	19.8	2406.4	535.9	15.1	158.	31.8
Case 4	117.2	0.0	117.2	2326.2	0.0	2326.2	535.9	15.1	158.	31.8
Case 5	159.7	0.0	159.7	2754.4	0.0	2754.4	671.2	19.8	208.	41.8
Case 6	160.2	0.0	160.2	2773.2	6.0	2779.2	671.2	19.8	208.	41.7
Case 7	145.6	0.0	145.6	2704.7	9.4	2714.1	671.1	19.8	208.	41.7
Case 8	145.0	0.0	145.0	2675.8	0.0	2675.8	671.1	19.8	208.	41.7
Case 9	117.4	0.0	117.4	2336.2	3.4	2339.7	535.9	15.1	158.	31.8
Case	132.0	0.0	132.0	2404.8	0.0	2404.8	536.0	15.1	158.	31.8

The percentage increase in the environmental impact after including the fire protection is calculated

Percentage increase in impact on Resource Use										
	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	%	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*
Case 1	38.7	-	38.7	10.6	-	10.6	0.0	0.0	0.0	0.3
Case 2	39.0	-	39.0	11.4	-	11.7	0.0	0.0	0.0	0.3
Case 3	1.5	-	1.5	2.9	-	3.8	0.0	0.0	0.0	-0.0
Case 4	0.4	-	0.4	0.3	-	0.3	0.0	0.0	0.0	0.0
Case 5	36.8	-	36.8	18.8	-	18.8	25.2	31.5	31.5	31.5
Case 6	37.1	-	37.1	19.6	-	19.9	25.2	31.5	31.5	31.5
Case 7	24.7	-	24.7	16.7	-	17.1	25.2	31.5	31.5	31.4
Case 8	24.1	-	24.1	15.4	-	15.4	25.2	31.5	31.5	31.4
Case 9	0.5	-	0.5	0.8	-	0.9	0.0	0.0	0.0	0.0
Case	13.0	-	13.0	3.7	-	3.7	0.0	0.0	0.0	0.1

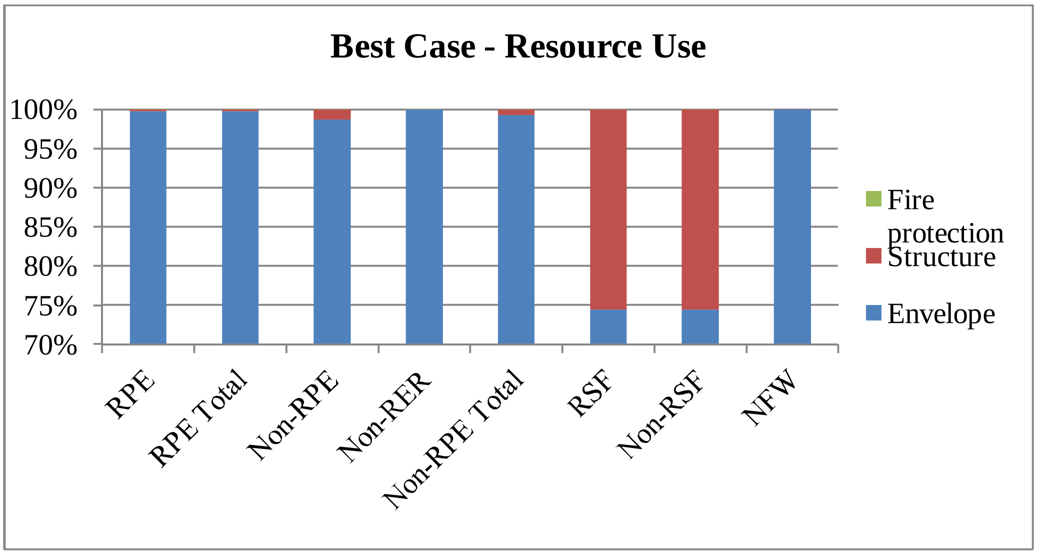
– The results are the same as that for Environmental impact. Case 9 is chosen as the Best case and Case 6 as the worst.

4.4.1. Best Case –Case 9

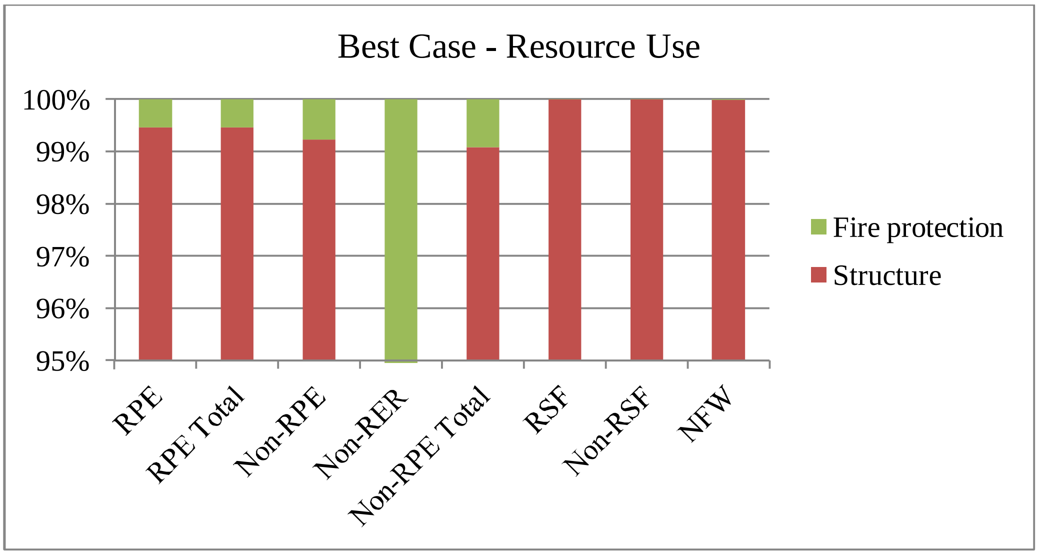
Case	For Columns	For Beams	For Truss Girder
Case 9	Intumescent	Spray	Spray

Percentage influence of components of the full model on Resource Use

		Percentage Change - Resource Use							
Full Model – With Envelope		RPE	RPE Total	Non RPE	Non RER	Non RPE Total	RSF	Non RSF	NFW
		%	%	%	%	%	%	%	%
Modules : Total A to D	Envelope	99.78	99.77	98.70	100.00	99.24	74.47	74.46	99.97
	Structure	0.21	0.23	1.29	0.00	0.75	25.53	25.54	0.03
	Fire	0.0012	0.0013	0.0100	0.0027	0.007	0.0001	0.0001	0.0000



		Percentage Change - Resource Use							
Full Model – Structural Frame Only		RPE	RPE Total	Non RPE	Non RER	Non RPE Total	RSF	Non RSF	NFW
		%	%	%	%	%	%	%	%
Modules : Total A to D	Structure	99.46	99.46	99.23	0.00	99.09	100.00	100.00	99.98
	Fire protection	0.539	0.539	0.768	100.0	0.914	0.000	0.000	0.016

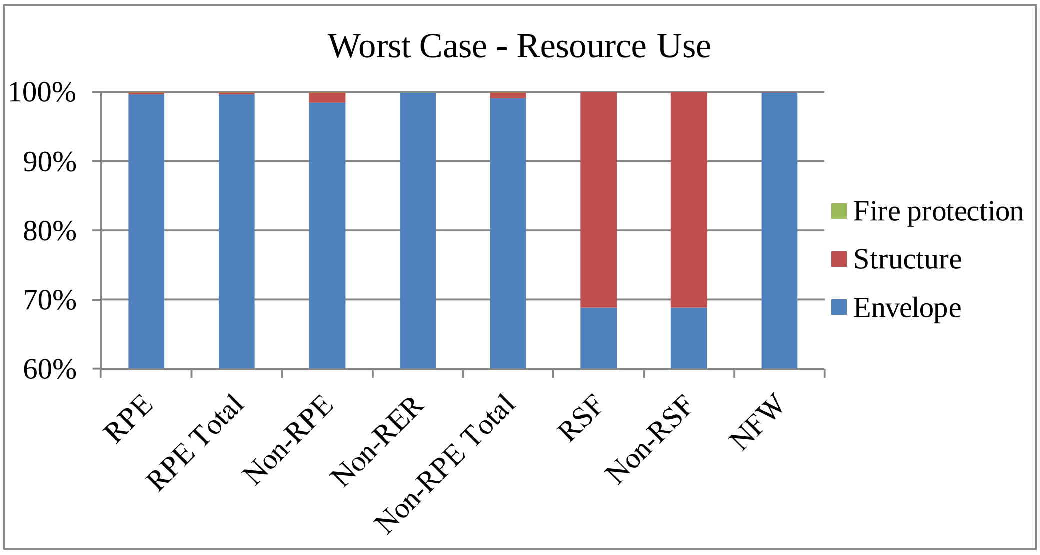


4.4.2. Worst Case

Case	For Columns	For Beams	For Truss Girder
Case 6	Boarding	Slim Floor	Intumescent

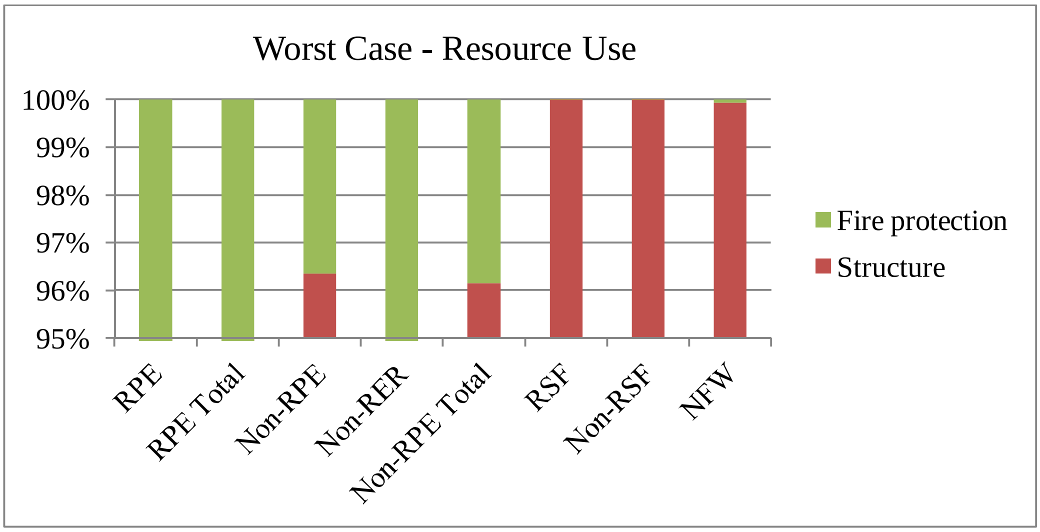
Percentage influence of components of the full model on Resource Use

		Percentage Change - Resource Use							
Full Model – With Envelope		RPE	RPE Total	Non RPE	Non RER	Non RPE Total	RSF	Non RSF	NFW
		%	%	%	%	%	%	%	%
Modules : Total A to D	Envelope	99.71	99.68	98.46	100.0	99.10	68.93	68.91	99.96
	Structure	0.27	0.29	1.49	0.00	0.87	31.07	31.09	0.04
	Fire	0.028	0.030	0.056	0.004	0.034	0.000	0.000	0.000



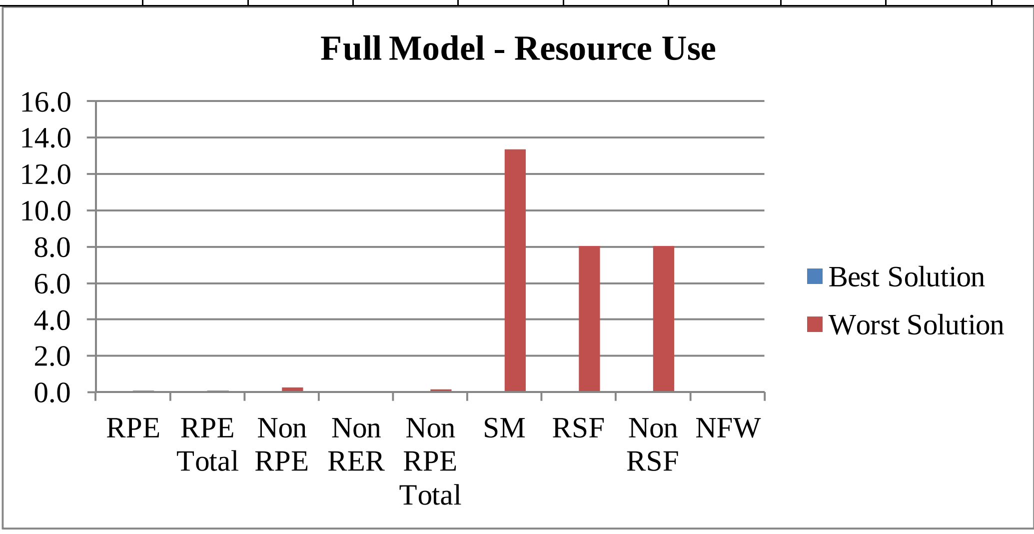
	Percentage Change - Resource Use

Full Model – Structural Frame Only		RPE	RPE Total	Non RPE	Non RER	Non RPE Total	RSF	Non RSF	NFW
		%	%	%	%	%	%	%	%
Modules : Total A to D	Structure	90.4	90.42	96.36	0.00	96.15	100.0	100.0	99.93
	Fire protection	9.58	9.58	3.64	100.00	3.85	0.00	0.00	0.07



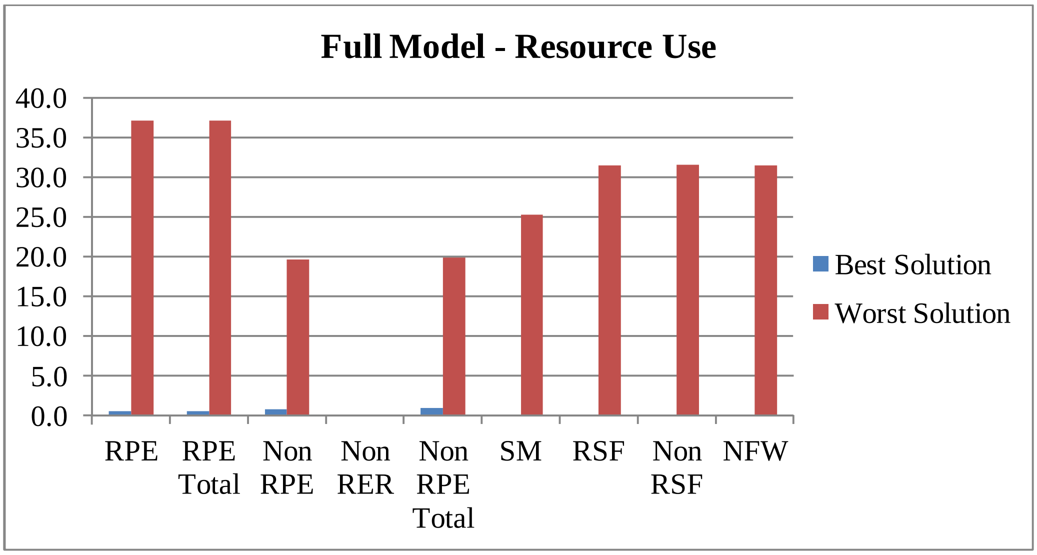
4.4.3. Comparison between the Best and Worst solutions

Percentage influence of fire protection when the full model is considered									
	RPE	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	%	%	%	%	%	%	%	%	%
Best Solution	0.001	0.001	0.010	0.003	0.007	0.000	0.000	0.000	0.000
Worst Solution	0.080	0.086	0.254	0.005	0.150	13.371	8.037	8.052	0.009



Percentage influence of fire protection when only the structural frame is considered

	RPE	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	%	%	%	%	%	%	%	%	%
Best Solution	0.542	0.542	0.774	-	0.922	0.000	0.000	0.000	0.016
Worst Solution	37.123	37.123	19.623	-	19.882	25.242	31.475	31.527	31.451



4.5. Waste categories

The indicators describing waste categories are

HWD	Hazardous waste disposed
Non-HWD	Non hazardous waste disposed
RWD	Radioactive waste disposed

Total Impact = Impact of Structural frame + Impact of Fire protection

Structural Frame - Full Model	Waste Categories		
	HWD	NHWD	RWD
	t/FU	*t/FU*	*t/FU*
Case Study	0.0165	521.9700	0.0807
Case 1	0.0191	568.5947	0.0811
Case 2	0.0191	567.9904	0.0814
Case 3	0.0165	523.1947	0.0818
Case 4	0.0166	526.0145	0.0807
Case 5	0.0261	623.0825	0.0811
Case 6	0.0261	622.4782	0.0814
Case 7	0.0252	607.6724	0.0815
Case 8	0.0253	608.9283	0.0810

Case 9	0.0166	525.3628	0.0809
Case 10	0.0174	540.1687	0.0808

The percentage increase in the environmental impact after including the fire protection is calculated

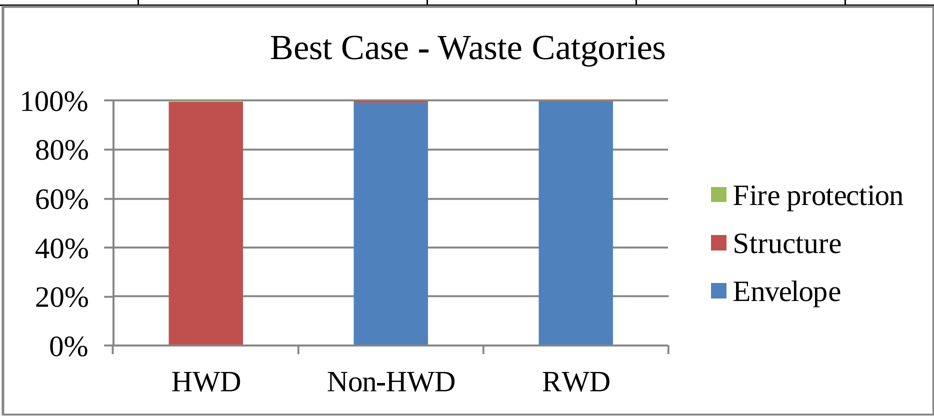
	Percentage increase in impact on Waste Categories		
	HWD	NHWD	RWD
	%	%	%
Case 1	15.89	8.93	0.50
Case 2	15.76	8.82	0.91
Case 3	0	0.23	1.34
Case 4	0.53	0.77	0.00
Case 5	57.97	19.37	0.48
Case 6	57.84	19.26	0.89
Case 7	52.66	16.42	0.96
Case 8	52.90	16.66	0.32
Case 9	0.42	0.65	0.23
Case 10	5.60	3.49	0.17

4.5.1. Best Case

Case	For Columns	For Beams	For Truss Girder
Case 9	Intumescent	Spray	Spray

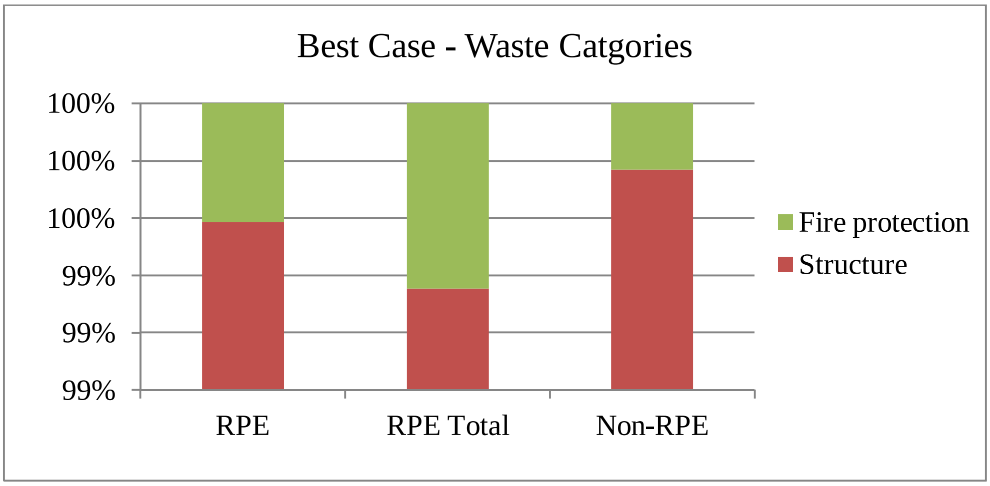
Percentage influence of components of the full model on Waste Categories

Full Model – With Envelope		Percentage Change – Waste Categories		
		HWD	NHWD	RWD
		%	%	%
Modules: Total A to D	Envelope	99.78	99.77	98.70
	Structure	0.21	0.23	1.29
	Fire protection	0.0012	0.0013	0.0100



	Percentage Change – Waste Categories

Full Model – Structural Frame Only		HWD	NHWD	RWD
		%	%	%
Modules: Total A to D	Structure	99.46	99.46	99.23
	Fire protection	0.539	0.539	0.768

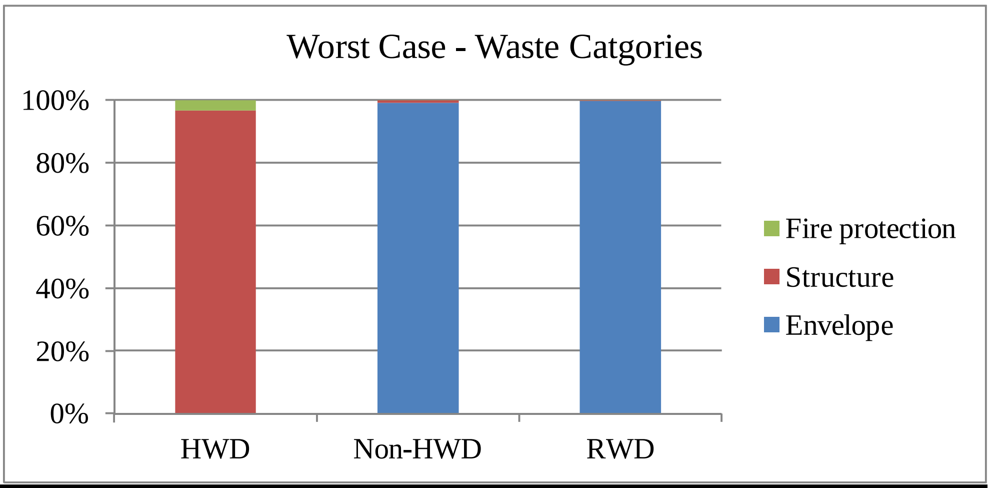


4.5.2. Worst Case

Case	For Columns	For Beams	For Truss Girder
Case 6	Boarding	Slim Floor	Intumescent

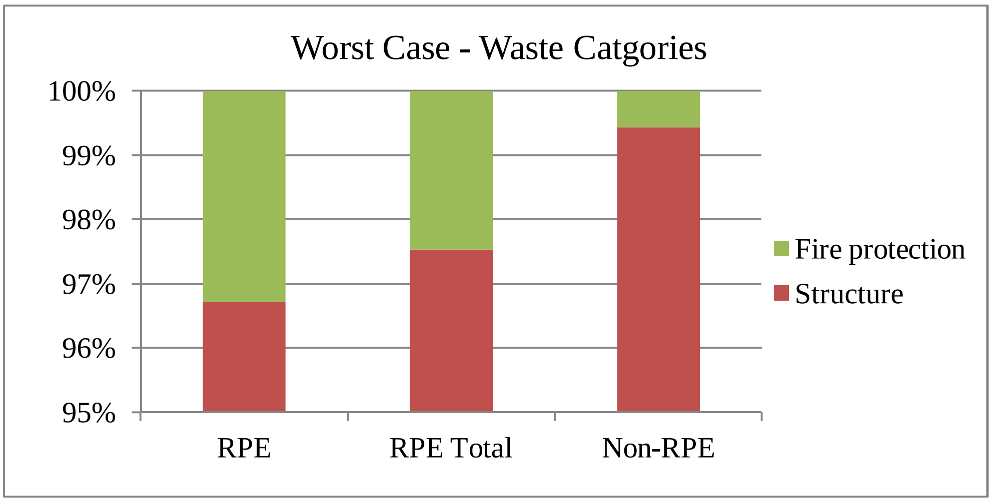
Percentage influence of components of the full model on Waste Categories

		Percentage Change – Waste Categories		
Full Model – With Envelope		HWD	NHWD	RWD
		%	%	%
Modules: Total A to D	Envelope	99.78	99.77	98.70
	Structure	0.21	0.23	1.29
	Fire protection	0.0012	0.0013	0.0100



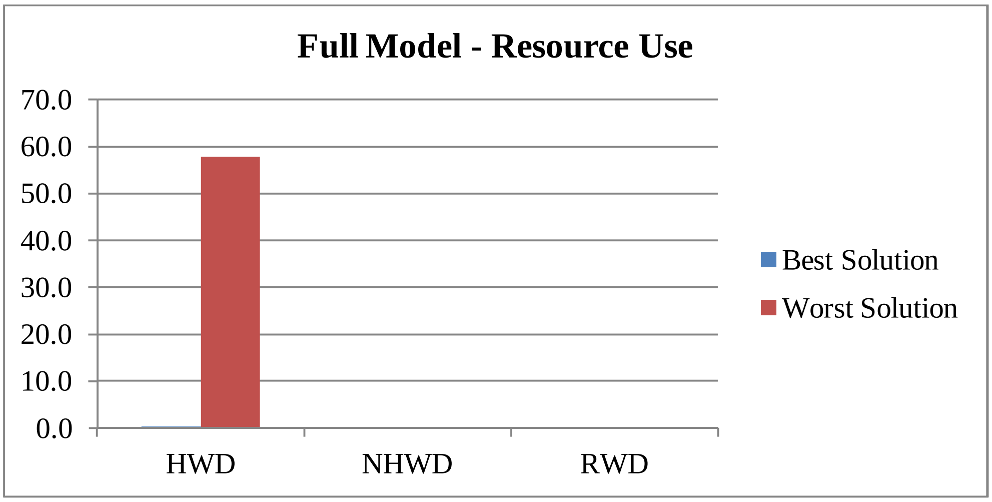
	Percentage Change – Waste Categories

Full Model – Structural Frame Only		HWD	NHWD	RWD
		%	%	%
Modules: Total A to D	Structure	99.46	99.46	99.23
	Fire protection	0.539	0.539	0.768



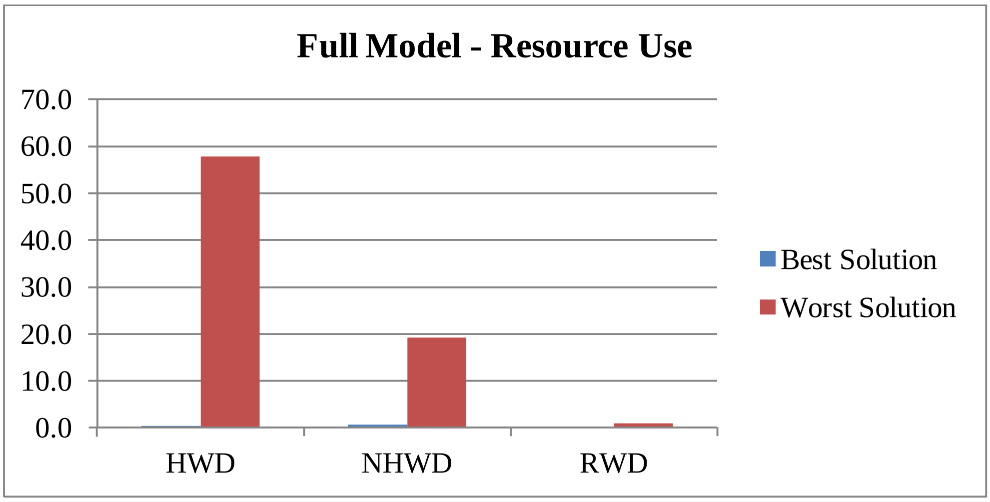
4.5.3. Comparison between the Best and Worst solutions

Percentage influence of fire protection when the full model is considered			
	HWD	NHWD	RWD
	%	%	%
Best Solution	0.416	0.005	0.000
Worst Solution	57.843	0.144	0.002



Percentage influence of fire protection when the full model is considered			
	HWD	NHWD	RWD

	%	%	%
Best Solution	0.416	0.650	0.230
Worst Solution	57.843	19.256	0.890



5. Observations and Summary

The multi-storey building cum sports hall chosen for this study gives us a wide range of results to study the performance in terms of sustainability. When comparing environmental impact, between the multi-storey building and the sports hall, it can be observed that in case of sports hall, the influence of fire protection is much higher when the LCA of only the structural frame is considered. This implies that the envelope of the sports hall (which includes the Use Phase) has a larger influence on the overall sustainability than the envelope in the multi-storey building.

By doing a comparative study of 10 different solutions which were a combination of slim flooring, boarding, intumescent and spray painting, we get an idea on the importance of these protection methods when sustainability of the building is concerned and how the different fire protection methods perform under sustainability. Among the fire solutions compared, spray protection has the best performance and is the most sustainable. Boarding has the worst performance after intumescent coating. Even though slim flooring can be better for fire design, easier construction and saves space, it has lower performance in case of sustainability. This is due to increase in quantity of steel and concrete.

Among the different fire solutions that were designed and compared, the best and worst solution in terms of its environmental performance were found. The worst fire solution can increase the environmental impact categories by 20 % when only the structural frames are considered for the full model (this excludes the building envelope and the use phase) whereas the best solution increases it only by about an average of 1%.

Table 5.1: Details of the best and worst fire protection solutions

Case	For Columns	For Beams	For Truss Girder
Case 6	Boarding	Slim Floor	Intumescent
Case 9	Intumescent	Spray	Spray

Table 5.2: Percentage Increase in Environmental Impact after designing for fire (full building model)

	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	%	%	%	%	%	%	%
Case 1	0.083	5.105	0.053	0.164	0.085	18.817	0.070
Case 2	0.090	5.293	0.060	0.220	0.094	0.082	0.078
Case 3	0.023	0.739	0.025	0.194	0.037	0.172	0.028
Case 4	0.002	0.148	0.001	0.011	0.007	77.875	0.003
Case 5	0.233	6.538	0.135	0.361	0.240	27.159	0.118
Case 6	0.239	6.727	0.142	0.417	0.250	8.425	0.126
Case 7	0.216	5.186	0.129	0.397	0.229	8.444	0.108
Case 8	0.206	4.902	0.118	0.310	0.215	43.759	0.096
Case 9	0.006	0.244	0.005	0.042	0.012	61.295	0.007
Case 10	0.029	1.784	0.018	0.062	0.033	61.275	0.025

Table 5.3: Percentage Increase in Environmental Impact after designing for fire (structural frame only)

	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	%	%	%	%	%	%	%
Case 1	7.07	21.95	7.84	11.05	6.43	-203.93	10.75
Case 2	7.61	22.76	8.90	14.82	7.15	-0.89	11.96
Case 3	1.94	3.18	3.67	13.03	2.78	-1.86	4.28
Case 4	0.20	0.64	0.21	0.74	0.54	-843.99	0.39
Case 5	19.80	28.11	19.92	24.30	18.23	-294.34	18.07
Case 6	20.34	28.92	20.98	28.08	18.94	-91.30	19.28
Case 7	18.36	22.30	19.06	26.75	17.35	-91.52	16.51
Case 8	17.53	21.08	17.41	20.89	16.27	-474.25	14.65
Case 9	0.49	1.05	0.80	2.83	0.90	-664.30	1.04
Case 10	2.47	7.67	2.73	4.16	2.50	-664.09	3.81

Overall the percentage influence of fire protection methods on the sustainability of the overall building is very low, about 0.01%. This is due to the reason that in the life of a building, most of the energy consumption is in the use phase (Module B). But if we do not consider the use phase, then the influence of the fire protection could be about 0.1% (average value) of the overall impact for the best solution and about 5 times higher for the worst solution. The range of values for each impact category are given below.

Table 5.4: Percentage influence of fire protection on the full model – Environmental Impact

	GWP	ODP	AP	EP	POCP	ADPF
	%	%	%	%	%	%
Best Fire Solution (Case 9)	0.006	0.244	0.005	0.042	0.012	0.007
Worst Fire Solution (Case6)	0.239	6.727	0.142	0.417	0.250	0.126

Table 5.5: Percentage influence of fire protection on the full model – Resource Use

	RPE	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	%	%	%	%	%	%	%	%	%
Best Fire Solution (Case 9)	0.001	0.001	0.01	0.003	0.007	0.00	0.00	0.00	0.000
Worst Fire Solution (Case6)	0.080	0.086	0.25	0.005	0.150	13.4	8.04	8.05	0.009

Table 5.6: Percentage influence of fire protection on the full model – Waste Categories

	HWD	NHWD	RWD
	%	%	%
Best Fire Solution (Case 9)	0.416	0.005	0.000
Worst Fire Solution (Case6)	57.843	0.144	0.002

6. Future Study

Through this work, an attempt has been made to understand the influence of design of fire protection on the sustainability of the buildings. The results obtained give us an idea on which methods are better. In this study, the impact values of the materials were added separately outside of the software which calculated only the LCA values of the building model. Hence it would be good to validate these results with advanced software which would take into account more parameters of the building model.

With a rising number of active and passive fire protection methods, it is also necessary to perform sustainability studies and develop environmental product declarations so that while designing a structure, it would be easier for the engineer to also design for sustainability. The impact of systems like sprinklers, which are very useful in active fire protection and also commonly used, could be checked for its environmental impact and resource use.

Also the fire safety requirements and performance differ for different building models. Skyscrapers require higher fire protection and industrial buildings also perform differently compared to the building model chosen for this study. Hence it would be interesting to perform a similar study on these different building types and compare the results. This way we could create a knowledge base on the best practices for fire design both in terms of fire safety and sustainability.

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8. Annex

Tables with Impact Values of all cases

8.1. Environmental Impact

Multi-storey Building

Multistorey building – Complete	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Module A	536.47	0.00	1.83	0.18	0.19	0.00	5146.77
Module B	7923.25	0.00	37.50	1.98	2.21	0.00	139472.82
Module C	29.50	0.00	0.11	0.03	0.02	0.00	314.00
Module D	-60.70	0.00	-0.17	-0.01	-0.03	0.00	-829.65
Total	8428.53	0.00	39.27	2.18	2.38	0.00	144103.94

Multistorey building – Structure only	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Module A	214.70	0.00	0.54	0.05	0.07	0.00	1987.50
Module B	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Module C	7.39	0.00	0.05	0.01	0.01	0.00	148.11
Module D	-31.70	0.00	-0.08	0.00	-0.02	0.00	-337.58
Total	190.40	0.00	0.51	0.06	0.06	0.00	1798.03

Multistorey building – Envelope Only	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Module A	321.77	4.26E-06	1.2931	0.12268	0.12102	0.0005404	3159.27
Module B	7923.25	7.11E-06	37.5	1.978	2.209	0.001091	139472.8
Module C	22.11	1.48E-06	0.0583	0.01533	0.01037	9.459E-06	165.89
Module D	-29	4.57E-07	-0.09304	-0.00337	-0.017109	-0.00029	-492.07
Total	8238.13	1.33E-05	38.7568	2.11258	2.3237	0.0013488	142305.9

Sport Hall

Sports Hall	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Module A	368.02	0.00	1.23	0.14	0.13	0.00	4044.94
Module B	9250.06	0.00	43.80	2.31	2.58	0.00	162828.49
Module C	15.91	0.00	0.08	0.03	0.01	0.00	225.39
Module D	-65.66	0.00	-0.17	-0.01	-0.04	0.00	-867.74
Total	9568.33	0.00	44.94	2.48	2.69	0.00	166231.1

Sports Hall – Structure Only	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Module A	37.07	0.00	0.11	0.01	0.01	0.00	403.86
Module B	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Module C	0.20	0.00	0.00	0.00	0.00	0.00	6.16
Module D	-3.56	0.00	-0.01	0.00	0.00	0.00	-38.34
Total	33.70	0.00	0.10	0.01	0.01	0.00	371.67

Sport Hall - Envelope

Sports Hall – Envelope only	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Module A	330.95	0.00	1.12	0.13	0.12	0.00	3641.08
Module B	9250.06	0.00	43.80	2.31	2.58	0.00	162828.49
Module C	15.71	0.00	0.08	0.03	0.01	0.00	219.23
Module D	-62.10	0.00	-0.16	0.00	-0.04	0.00	-829.40
Total	9534.63	0.00	44.84	2.47	2.68	0.00	165859.40

LCA of Structural Frame – Multistorey+Sports Hall

Full Building – Structure only	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Module A	238.02	0.00	0.61	0.06	0.08	0.00	2241.46
Module B	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Module C	7.51	0.00	0.05	0.01	0.01	0.00	151.99
Module D	-33.93	0.00	-0.09	0.00	-0.02	0.00	-361.69
Total	211.59	0.00	0.57	0.07	0.07	0.00	2031.76

Composite slab

Multi storey with Slim floor - Structure	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Module A	274.27	0.00	0.68	0.07	0.09	0.00	2502.20
Module B	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Module C	9.52	0.00	0.06	0.02	0.01	0.00	189.54
Module D	-56.52	0.00	-0.14	-0.01	-0.03	0.00	-599.75
Total	227.28	0.00	0.61	0.08	0.07	0.00	2091.98

Full structure with Slim floor –	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Module A	297.60	0.00	0.75	0.07	0.10	0.00	2756.24
Module B	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Module C	9.65	0.00	0.06	0.02	0.01	0.00	193.42
Module D	-58.76	0.00	-0.14	-0.01	-0.03	0.00	-623.87
Total	248.49	0.00	0.67	0.08	0.08	0.00	2325.79

LCA for Fire Protection

Boarding

Boarding	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	kg CO_2 equiv/FU	*kg CFC11 equiv/FU*	*kg SO_2 equiv/FU*	*kg $(PO_4)^{3-}$ equiv/FU*	*kg Ethene equiv/FU*	*kg Sb equiv/FU*	*MJ/FU*
Module A	3.640	0.000	0.011	0.001	0.001	0.000	53.100
Module B	-	-	-	-	-	-	-
Module C	0.019	0.000	0.000	0.001	0.000	0.000	0.230
Module D	-	-	-	-	-	-	-
Total	3.659	0.000	0.011	0.002	0.001	0.000	53.330

Intumescent

Intumescent	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	kg CO_2 equiv/FU	*kg CFC11 equiv/FU*	*kg SO_2 equiv/FU*	*kg $(PO_4)^{3-}$ equiv/FU*	*kg Ethene equiv/FU*	*kg Sb equiv/FU*	*MJ/FU*
Module A	2.514	0.000	0.013	0.006	0.001	0.000	53.245
Module B	-	-	-	-	-	-	-
Module C	-	-	-	-	-	-	-
Module D	-	-	-	-	-	-	-
Total	2.514	0.000	0.013	0.006	0.001	0.000	53.245

Spray

Spray	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	kg CO_2 equiv/FU	*kg CFC11 equiv/FU*	*kg SO_2 equiv/FU*	*kg $(PO_4)^{3-}$ equiv/FU*	*kg Ethene equiv/FU*	*kg Sb equiv/FU*	*MJ/FU*
Module A	0.098	0.000	0.000	0.000	0.000	0.001	1.757
Module B	-	-	-	-	-	-	-
Module C	0.007	0.000	0.000	0.000	0.000	0.000	0.198
Module D	-	-	-	-	-	-	-
Total							

Best Scenario Case – 9

- The results for only the multi-storey part of the model. The impact of each component – Structural frame, Fire protection and Envelope is presented

		Environmental Impact						
Multi-storey building		GWP	ODP	AP	EP	POCP	ADPE	ADPF
Modules		*ton CO_2 equiv*	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Total A to D	Envelope	8238.13	0.00	38.76	2.11	2.32	0.00	142305.91
	Structure	190.40	0.000	0.509	0.063	0.059	0.000	1798.03
	Fire	0.59	0.000	0.002	0.001	0.000	0.002	11.92
	Total	8429.12	0.000	39.27	2.18	2.38	0.003	144115.86

- The results for only the sports hall

		Environmental Impact						
Sports Hall		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Total A to D	Envelope	9534.63	0.00	44.84	2.47	2.68	0.00	165859.40
	Structure	33.70	0.000	0.097	0.009	0.012	0.000	371.67
	Fire	0.631	0.000	0.003	0.001	0.000	0.001	13.107
	Total	9568.96	0.00	44.94	2.48	2.69	0.00	166244.18

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- Results for the full model, including the multi-storey and the sports hall

		Environmental Impact						
Full Model		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Total A to D	Envelope	17772.76	0.00	83.60	4.58	5.00	0.0052	308165.31
	Structure	211.59	0.000	0.569	0.069	0.067	-0.0004	2031.76
	Fire	1.04	0.000	0.005	0.002	0.001	0.0029	21.19
	Total	17985.39	0.00	84.17	4.65	5.07	0.0077	310218.26

Worst Scenario – Case 6

		Environmental Impact						
Multi-storey building		GWP	ODP	AP	EP	POCP	ADPE	ADPF
Modules		*ton CO_2 equiv*	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Total A to D	Envelope	8238.13	1.33E-05	38.7568	2.11258	2.3237	0.0013488	142305.9
	Structure	227.28	9.01E-06	0.6064	0.07731	0.06984	8.498E-05	2091.98
	Fire protection	3.46E+00	4.16E-07	1.03E-02	1.75E-03	9.80E-04	3.37E-07	5.04E+01
	Total	8468.87	0.0000227	39.37	2.19	2.39	0.0014	144448.27

		Environmental Impact						
Sports Hall		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Total A to D	Envelope	9534.63	1.38E-05	44.83893	2.46575	2.67629	0.0038691	165859.4
	Structure	33.7	1.43E-06	0.09709	0.009278	0.01208	-0.0002004	371.67
	Fire protection	3.60E+00	3.62E-07	1.33E-02	3.92E-03	1.23E-03	2.72E-06	6.07E+01
	Total	9571.928	1.55E-05	44.94936	2.478946	2.6896	0.0036715	166291.7

		Environmental Impact						
Full Model		GWP	ODP	AP	EP	POCP	ADPE	ADPF
		ton CO_2 equiv	*ton CFC11 equiv*	*ton SO_2 equiv*	*ton $(PO_4)^{3-}$ equiv*	*ton Ethene equiv*	*ton Sb equiv*	*GJ NCV*
Total A to D	Envelope	17772.760	0.000	83.596	4.578	5.000	0.005218	308165.310
	Structure	248.490	0.000	0.668	0.083	0.078	-0.000041	2325.790
	Fire	6.133	0.000	0.021	0.005	0.002	0.000003	97.615
	Total	18027.38	0.00	84.28	4.67	5.08	0.01	310588.72

8.2. Resource Use

Multi-storey Building

Multistorey building	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	GJ NCV	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*1000m^3*
Module A	2520.08	655.94	138.21	3065.97	5.15	3071.13	1005.17	31.43	330.80	11694.00
Module B	23265.91	0.00	23265.91	80605.30	59220.72	139826.02	0.00	2.85	29.88	30265.08
Module C	37.79	2.17	6.76	311.43	0.00	311.43	0.00	0.00	0.01	1290.97
Module D	-498.63	13.39	4.19	-337.36	0.00	-337.36	-8.77	0.00	0.00	-279.29
Total	25325.15	671.51	23415.08	83645.33	59225.87	142871.21	996.41	34.28	360.68	42970.75

Multistorey building – Structure only	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	GJ NCV	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*1000m^3*
Module A	97.09	0.00	97.09	2224.20	0.00	2224.20	529.39	15.06	158.47	14.67
Module B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Module C	3.68	0.00	3.68	161.82	0.00	161.82	0.00	0.00	0.00	18.88
Module D	4.49	0.00	4.49	-334.2	0.00	-334.2	-8.77	0.00	0.00	-1.82
Total	105.26	0.00	105.26	2051.81	0.00	2051.81	520.63	15.06	158.47	31.73

Multistorey building – Envelope Only	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	GJ NCV	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*1000m^3*
Module A	2422.99	655.94	41.12	841.77	5.15	846.93	475.78	16.37	172.33	11679.33
Module B	23265.91	0.00	23265.91	80605.30	59220.72	139826.02	0.00	2.85	29.88	30265.08
Module C	34.11	2.17	3.08	149.60	0.00	149.60	0.00	0.00	0.01	1272.09
Module D	-503.12	13.39	-0.30	-3.15	0.00	-3.15	0.00	0.00	0.00	-277.47
Total	25219.89	671.51	23309.82	81593.52	59225.87	140819.40	475.78	19.22	202.21	42939.02

Sport Hall

Sports Hall	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW

	GJ NCV	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*1000m³*
Module A	2836.30	382.29	67.61	1397.73	4.64	1402.37	26.97	21.37	224.90	38594.66
Module B	27161.95	0.00	27161.95	94103.20	69137.63	163240.83	0.00	3.33	34.88	35333.17
Module C	13.36	0.16	5.01	240.18	0.00	240.18	0.00	0.00	0.01	163.74
Module D	-842.89	34.20	-2.32	-48.86	0.00	-48.86	-2.67	0.00	0.00	22.89
Total	29168.74	416.65	27232.26	95692.24	69142.27	164834.51	24.30	24.70	259.79	74114.44

Sports Hall – Structure Only	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	GJ NCV	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*1000m³*
Module A	19.93	0.00	19.93	461.50	0.00	461.50	26.97	0.00	0.00	0.05
Module B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Module C	0.26	0.00	0.26	6.19	0.00	6.19	0.00	0.00	0.00	0.01
Module D	-1.85	0.00	-1.85	-43.92	0.00	-43.92	-2.67	0.00	0.00	0.00
Total	18.34	0.00	18.34	423.77	0.00	423.77	24.30	0.00	0.00	0.05

Sport Hall - Envelope

Sports Hall – Envelope only	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	GJ NCV	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*1000m³*
Module A	2816.37	382.29	47.68	936.23	4.64	940.87	0.00	21.37	224.90	38594.61
Module B	27161.95	0.00	27161.95	94103.20	69137.63	163240.83	0.00	3.33	34.88	35333.17
Module C	13.10	0.16	4.75	233.99	0.00	233.99	0.00	0.00	0.01	163.73
Module D	-841.04	34.20	-0.47	-4.94	0.00	-4.94	0.00	0.00	0.00	22.89
Total	29150.40	416.65	27213.92	95268.47	69142.27	164410.74	0.00	24.70	259.79	74114.39

LCA of Structural Frame – Multistorey+Sports Hall

Full Building – Structure only	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	GJ NCV	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*$1000m^3$*
Module A	109.63	0.00	109.63	2514.40	0.00	2514.40	546.35	15.06	158.5	14.71
Module B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Module C	3.83	0.00	3.83	165.73	0.00	165.73	0.00	0.00	0.00	18.88
Module D	3.34	0.00	3.34	-361.84	0.00	-361.84	-10.44	0.00	0.00	-1.83
Total	116.80	0.00	116.80	2318.30	0.00	2318.30	535.91	15.06	158.5	31.76

Composite slab

Multi storey with Slim floor - Structure	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	GJ NCV	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*$1000m^3$*
Module A	110.02	0.00	110.02	2764.43	0.00	2764.42	664.10	19.81	208.42	19.45
Module B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Module C	4.64	0.00	4.64	207.53	0.00	207.53	0.00	0.00	0.00	24.80
Module D	18.61	0.00	18.61	-566.33	0.00	-566.33	-8.26	0.00	0.00	-2.56
Total	133.26	0.00	133.26	2405.61	0.00	2405.60	655.84	19.81	208.42	41.70

Full structure with Slim floor – Structure only	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	GJ NCV	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*$1000m^3$*
Module A	122.55	0.00	122.55	3054.73	0.00	3054.73	681.07	19.80	208.43	19.49
Module B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Module C	4.80	0.00	4.80	211.43	0.00	211.43	0.00	0.00	0.00	24.81
Module D	17.45	0.00	17.45	-593.98	0.00	-593.98	-9.93	0.00	0.00	-2.57
Total	144.81	0.00	144.81	2672.19	0.00	2672.19	671.14	19.80	208.43	41.72

LCA for Fire Protection

Boarding

Boarding	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	MJ NCV	*MJ NCV*	*MJ NCV*	*MJ NCV*	*MJ NCV*	*MJ NCV*	*kg*	*MJ*	*MJ*	*m^3*
Module A	11.10	0.00	11.10	59.90	0.00	59.90	0.03	0.00	0.00	0.02
Module B	-	-	-	-	-	-	-	-	-	-
Module C	0.00	0.00	0.00	0.23	0.00	0.23	0.00	0.00	0.00	0.00
Module D	-	-	-	-	-	-	-	-	-	-
Total	11.10	0.00	11.10	60.13	0.00	60.13	0.03	0.00	0.00	0.02

Intumescent

Intumescent	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	MJ NCV	*MJ NCV*	*MJ NCV*	*MJ NCV*	*MJ NCV*	*MJ NCV*	*kg*	*MJ*	*MJ*	*m^3*
Module A	1.05	0.00	1.05	41.80	12.12	53.92	0.00	0.00	0.00	
Module B	-	-	-	-	-	-	-	-	-	-
Module C	-	-	-	-	-	-	-	-	-	-
Module D	-	-	-	-	-	-	-	-	-	-
Total	1.05	0.00	1.05	41.80	12.12	53.92	0.00	0.00	0.00	

Spray

Spray	RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
	MJ NCV	*MJ NCV*	*MJ NCV*	*MJ NCV*	*MJ NCV*	*MJ NCV*	*kg*	*MJ*	*MJ*	*m^3*
Module A	0.10	0.00	0.10	1.75	0.00	1.76				0.00
Module B	-	-	-	-	-	-	-	-	-	-
Module C	0.00	0.00	0.00	0.20	0.00	0.20				0.00
Module D	-	-	-	-	-	-	-	-	-	-
Total	0.14	0.03	0.00	0.03	0.16	0.00	0.16	0.00	0.00	0.00

Best Scenario Case – 9

- Results for the full model, including the multi-storey and the sports hall

Full Model		RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
Modules		*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*1000* m^3
Total A to D	Envelope	54370.29	1088.16	50523.74	176861.99	128368.14	305230.14	475.78	43.92	462.00	117053.41
	Structure	116.80	0.00	116.80	2318.30	0.00	2318.30	535.91	15.06	158.47	31.76
	Fire protection	0.63	0.00	0.63	17.95	3.41	21.38	0.00	0.00	0.00	0.01
	Total	54487.72	1088.16	50641.17	179198.24	128371.55	307569.82	1011.69	58.98	620.47	117085.18

Worst Scenario – Case 6

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- Results for the full model, including the multi-storey and the sports hall

Full Model		RPE	RER	RPE Total	Non RPE	Non RER	Non RPE Total	SM	RSF	Non RSF	NFW
Modules		*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*GJ NCV*	*ton*	*GJ*	*GJ*	*1000* m^3
Total A to D	Envelope	54370.29	1088.16	50523.74	176862	128368.1	305230.1	475.78	43.92	462	117053.4
	Structure	144.81	0	144.81	2672.19	0	2672.19	671.14	19.8	208.43	41.72
	Fire protection	1.54E+01	0.00E+00	1.54E+01	1.01E+02	6.00E+00	1.07E+02	4.56E-02	6.89E-05	7.22E-04	2.88E-02
	Total	54530.45	1088.16	50683.9	179635.2	128374.1	308009.4	1146.966	63.72007	670.4307	117095.2

8.3. Waste Categories

Multi-storey Building

Multistorey building	HWD	NHWD	RWD
	ton	*ton*	*ton*
Module A	0.02	819.59	0.10
Module B	0.00	31610.04	20.52
Module C	0.00	21.07	0.00
Module D	0.00	-79.89	-0.01
Total	0.02	32370.81	20.61

Multistorey building – Structure only	HWD	NHWD	RWD
	ton	*ton*	*ton*
Module A	0.02	541.72	0.08
Module B	0.00	0.00	0.00
Module C	0.00	12.05	0.00
Module D	0.00	-79.89	-0.01
Total	0.02	473.88	0.07

Multistorey building – Envelope Only	HWD	NHWD	RWD
	ton	*ton*	*ton*
Module A	0.00	75.92	0.01
Module B	0.00	31610.04	20.52
Module C	0.00	9.02	0.00
Module D	0.00	0.00	0.00
Total	0.00	31694.98	20.53

Sport Hall

Sports Hall	HWD	NHWD	RWD
	ton	*ton*	*ton*
Module A	0.00	439.82	0.04
Module B	0.00	36903.36	24.00
Module C	0.00	11.32	0.00
Module D	0.00	-8.13	0.00
Total	0.00	37346.38	24.04

Sports Hall – Structure Only	HWD	NHWD	RWD
	ton	*ton*	*ton*
Module A	0.00	81.40	0.02
Module B	0.00	0.00	0.00
Module C	0.00	3.20	0.00
Module D	0.00	-8.13	0.00
Total	0.00	76.48	0.02

Sport Hall - Envelope

Sports Hall – Envelope only	HWD	NHWD	RWD
	ton	*ton*	*ton*
Module A	0.00	358.42	0.02
Module B	0.00	36903.36	24.00
Module C	0.00	8.12	0.00
Module D	0.00	0.00	0.00
Total	0.00	37269.90	24.02

LCA of Structural Frame – Multistorey+Sports Hall

Full Building – Structure only	HWD	NHWD	RWD
	ton	*ton*	*ton*
Module A	0.02	592.91	0.10
Module B	0.00	0.00	0.00
Module C	0.00	14.07	0.00
Module D	0.00	-85.01	-0.01
Total	0.02	521.97	0.08

Composite slab

Multi storey with Slim floor - Structure	HWD	NHWD	RWD
	ton	*ton*	*ton*
Module A	0.03	691.99	0.09
Module B	0.00	0.00	0.00
Module C	0.00	13.43	0.00
Module D	0.00	-146.45	-0.02
Total	0.02	558.98	0.07

Full structure with Slim floor – Structure only	HWD	NHWD	RWD
	ton	*ton*	*ton*
Module A	0.03	743.20	0.10
Module B	0.00	0.00	0.00

Module C	0.00	15.45	0.00
Module D	0.00	-151.57	-0.02
Total	0.03	607.09	0.08

LCA for Fire Protection

Boarding

Boarding	HWD	NHWD	RWD
	kg	*kg*	*kg*
Module A	0.00	0.24	0.00
Module B	-	-	-
Module C	0.00	11.00	0.00
Module D	-	-	-
Total	0.00	11.24	0.00

Intumescent

Intumescent	HWD	NHWD	RWD
	kg	*kg*	*kg*
Module A	-	0.75	0.00
Module B	-	-	-
Module C	-	-	-
Module D	-	-	-
Total	0.00	0.75	0.00

Spray

Spray	HWD	NHWD	RWD
	kg	*kg*	*kg*
Module A	0.00	0.00	
Module B	-	-	-
Module C	-	1.00	-
Module D	-	-	-
Total	0.00	0.00	0.03

Best Scenario Case – 9

- Results for the full model, including the multi-storey and the sports hall

Full Model		HWD	NHWD	RWD
Modules		*ton*	*ton*	*ton*
Total A to D	Envelope	0.00	69166.83	44.57
	Structure	0.02	521.97	0.08
	Fire protection	0.00	3.39	0.00
	Total	0.02	69692.19	44.65

Worst Scenario – Case 6

- Results for the full model, including the multi-storey and the sports hall

Full Model		HWD	NHWD	RWD
Modules		*ton*	*ton*	*ton*
Total A to D	Envelope	0	69166.83	44.56582
	Structure	0.025222	607.09	0.080954
	Fire protection	8.57E-04	1.54E+01	4.61E-04
	Total	0.026079	69789.31	44.64723