ABSTRACT

Title of Thesis: ASSESSING THE VALIDITY OF THE VERIFICATION METHOD AS A DESIGN TOOL

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The Verification Method (VM) as a design tool is becoming more widespread, resulting in a need for a critique of the concepts behind the method. This project provides the critique by extracting examples from the design processes and solutions of a building being designed using three different approaches: Performance-Based Design, Prescriptive Methods and the VM.

The main perceived advantages of the VM is its time efficiency, accessibility and flexibility, while the observed weaknesses include substitution of the designer, the level of under- and over-design and its lack of robustness of the performance criteria and guidance in areas such as fire modeling. It is uncovered how the VM is a design method rather than a tool to demonstrate compliance with the performance requirements of building codes, which was the original objective of the VM. The Verification Method must return to its original intentions in order to ensure its validity as a design tool.

ASSESSING THE VALIDITY OF THE VERIFICATION METHOD AS A DESIGN TOOL

by

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Table of Contents

Chapter 1 Introduction 1
1.1 Verification Method 2 in New Zealand 4
1.2 Fire Safety Approaches in Australia, USA and UK 7
1.2.1 Australia 7
1.2.2 USA 8
1.2.3 United Kingdom 9
1.3 Objective of Research 9
1.4 Report overview 10
Chapter 2 Summary of Existing Fire Safety Verification Method 12
2.1 Introduction 12
2.2 Occupant Characteristics 13
2.2.1 Occupant Number and Design Occupant 13
2.2.2 RSET 17
2.2.3 Requirements for Delayed Evacuation Strategies 25
2.2.4 Fire Modeling to determine ASET 25
2.3 Design Fires 26
2.3.1 Theory behind the Idealized Design Fire Curve 28
2.3.2 Pre-flashover Design Fires 29
2.3.3 Post-Flashover Design Fires 30
2.3.4 Full Burnout Design Fires 31
2.3.5 Fire Modeling Assumptions and Procedures 32
2.4 Design Scenarios 34
2.4.1 BE: Fire Blocks Exit 36
2.4.2 UT: Fire in Normally Unoccupied Room 37
2.4.3 CS: Fire in Concealed Space 39
2.4.4 SF: Smoldering Fire 40
2.4.5 HS: Horizontal Fire Spread 41
2.4.6 VS: Vertical Fire Spread 43
2.4.7 IS: Rapid Fire Spread involving Internal Surface Linings 44

2.4.8 FI: Fire Brigade Intervention ... 46
2.4.9 UF: Unexpected Catastrophic Failure ... 47
2.4.10 CF: Challenging Fire ... 48
2.4.11 RC: Robustness Check ... 49
2.4.12 SS: Structural Stability and Other Property ... 50
Chapter 3 Execution of Performance-Based Design ... 52
3.1 Building Characteristics ... 52
3.1.1 Basement Levels – Car Park ... 53
3.1.2 Ground Floor – Retail Story ... 54
3.1.3 Upper Floors – Office & Library ... 55
3.2 Occupant Characteristics ... 56
3.3 Fire Strategy ... 57
3.4 Design Goals, Objectives and Performance Criteria ... 60
3.4.1 Objectives ... 60
3.4.2 Performance Criteria ... 61
3.5 Design Fire Scenarios ... 63
3.5.1 Car Park ... 65
3.5.2 Office spaces ... 69
3.5.3 Retail Space on Ground Floor ... 72
3.5.4 Library ... 73
3.6 Trial Designs ... 75
3.6.1 Retail Space ... 75
3.6.2 Car Park & Offices ... 79
3.7 Methodology ... 79
3.7.1 RSET and Pathfinder ... 80
3.7.2 ASET and CFAST ... 82
3.7.3 Fire Dynamics Simulator (FDS) ... 83
3.8 System Performance Evaluation ... 84
3.8.1 ASET/RSET Analysis for Retail Space ... 85
3.8.2 ASET/RSET Analysis for Office Floors (L1-L7) ... 99
3.8.3 ASET/RSET Analysis for Basement Floors (B1-B2) ... 114

3.8.4 Structural Integrity ... 121
3.9 Final Design ... 122
3.9.1 Basement Levels (B1-B2) ... 123
3.9.2 Ground Floor ... 124
3.9.3 Upper floors (L1-L7) ... 125
Chapter 4 Execution of Prescriptive Designs ... 127
4.1 AU ... 128
4.1.1 Principal Building and Occupant Characteristics ... 128
4.1.2 Fire Safety System ... 132
4.2 USA ... 136
4.2.1 Principal Building and Occupant Characteristics ... 136
4.2.2 Fire Safety System ... 140
4.3 UK ... 144
4.3.1 Principal Building and Occupant Characteristics ... 144
4.3.2 Fire Safety System ... 148
4.4 Comparison ... 153
4.4.1 Comparison of Outcomes ... 154
4.4.2 Comparison to the Performance-based Design ... 156
Chapter 5 Execution of Verification Method ... 158
5.1 Summary of Report ... 158
5.1.1 General Assumptions ... 159
5.1.2 BE1 – Fire blocks exit on a typical office floor level ... 162
5.1.3 UT1 – Fire in a storage room in a typical office level ... 162
5.1.4 UT2 - Fire in a storage room in a retail area ... 164
5.1.5 CS1 – Fire in ceiling space ... 165
5.1.6 CF1 – Challenging Fire in Car Park ... 167
5.1.7 CF2 – Challenging Fire in Retail Area ... 168
5.1.8 CF3, CF4 & CF5 – Challenging Fires in office area ... 170
5.1.9 RC1-RC10 – Robustness Check ... 171
5.1.10 SS – Structural Stability Check ... 172
5.1.11 IS2 – Fire Spread involving Internal Finishes ... 172

5.1.12 HS1 & HS2 – Horizontal Fire Spread 172
5.1.13 VS – Vertical Fire Spread 173
5.1.14 FI1 – Fire Brigade Intervention 173
5.1.15 Results 173
5.2 Reevaluation of Failed Design Scenarios 176
5.3 Results 177
Chapter 6 Results, Critique & Future Work 182
6.1 Results 182
6.2 Critique 187
6.2.1 Perceived or Desired Advantages 187
6.2.2 Observed Weaknesses 189
6.2.3 Conclusion 196
6.3 Future Work 197
Appendix A Time Equivalence Calculation 198
Appendix B Comparison Study 207
Appendix C Reevaluation of Failed Design Scenarios 232
Appendix D RSET Manual Calculations (Made by UQ) 274
Appendix E ASET Zone Model (Made by UQ) 278
References 284

List of Tables

Table 2-1: Occupant Densities used in the VM, taken from BCA Table D1.13. 15

Table 2-2: Occupant types, N = No impairment, S/P = Severe, profound impairment. 16

Table 2-3: Type C occupant characteristics. 16

Table 2-4: Detection times for manually activated detection systems. 18

Table 2-5: Detector criteria defined by the VM. 19

Table 2-6: Pre-movement activity times as defined in the VM. 22

Table 2-7: Maximum speeds for vertical travel for type A and B occupants. 22

Table 2-8: Boundary layer width of exit components. 24

Table 2-9: Pre-flashover design fire characteristics 30

Table 2-10: Design fire loads for use in modeling fires. 31

Table 2-11: All design scenarios defined by the VM. 36

Table 2-12: Horizontal fire spread - Building on adjacent allotments. 42

Table 2-13: Horizontal fire spread - Buildings on the same allotment. 42

Table 2-14: Classification of external walls – Vertical fire spread. 44

Table 2-15: Classification of external walls - Building to building spread. 44

Table 2-16: Internal surface lining requirements. 45

Table 2-17: Facilities for fire brigade intervention. 47

Table 3-1: Goals, objectives and performance criteria. 61

Table 3-2: Statistical data for the peak HRR, the time to peak and the total energy released for a medium sized car according to M. Z. M. Tohir's research [33]. 66

Table 3-3: Design fuel loads for offices areas from IFEG 2005. 69

Table 3-4: Design fuel loads for retails areas from IFEG 2005. 72

Table 3-5: Design fuel loads for libraries from IFEG 2005. 74

Table 3-6: Material characteristics for the compartment boundaries. 86

Table 3-7: Characteristics for different fuel types that will be tested in the CFAST model to determine the most conservative type of fuel for the design fire. 87

Table 3-8: Detection and pre-movement times for the small shop 89

Table 3-9: Evacuation time for various constant velocities. 91

Table 3-10: RSETs and ASETs when the lower velocity fractile is used. 92
Table 3-11: RSETs and ASETs when the upper velocity fractile is used. 92
Table 3-12: CFAST material characteristics for the compartment boundaries on the office floors. 100
Table 3-13: Design fire characteristics for the different fuel types on of office floors. 101
Table 3-14: FDS material characteristics for the compartment boundaries on the office floors. 103
Table 3-15: Evacuation time for the office floor for exit widths = 160 cm. 109
Table 3-16: ASETs and RSETs for the various design fire scenarios. The pre-movement time is the 90 percentage fractile. The velocity is normal distributed. ... 109
Table 3-17: Properties for the fuel used in the vehicle design fire. 116
Table 3-18: Evacuation time based on the mean velocity and the velocities two standard deviations away. 118
Table 3-19: RSETs and ASETs when the lower velocity fractile is used. 119
Table 3-20: RSETs and ASETs when the upper velocity fractile is used. 119
Table 3-21: Safety factors of the basement floor. 124
Table 3-22: Safety factors of the ground floor. 125
Table 3-23: Safety factors of office floors. 126
Table 4-1: Building characteristics. 131
Table 4-2: Occupant characteristics. 131
Table 4-3: Occupant warning system, fire brigade call out and lift homing matrix. 134
Table 4-4: Building characteristics. 139
Table 4-5: Occupant characteristics. 139
Table 4-6: Building characteristics. 147
Table 4-7: Occupant characteristics. 148
Table 5-1: Assumptions for manual RSET calculations. 160
Table 5-2: Assumptions for zone modeling calculations for ASET. 161
Table 5-3: Assumed sequence of events according to the FPA report. 164
Table 5-4: Assumed sequence of events according to the FPA report. 165
Table 5-5: Assumed sequence of events according to the FPA report. 166

Table 5-6: Assumed sequence of events according to the FPA report. 168
Table 5-7: Assumed sequence of events according to the FPA report. 169
Table 5-8: Assumed sequence of events according to the FPA report. 171
Table 5-9: Summary of results from the FPA report. 175
Table 5-10: Summary of results from the reevaluation of the design scenarios. The full set of results and calculations can be found in Appendix C. 181
Table 6-1: Summary of results for ground floor (Retail space). VAS = Voice Alarm Signal 184
Table 6-2: Summary of results for the basement (Car parking space). 185
Table 6-3 Summary of results for level L1 – L7 (Office and library area). VAS = Voice Alarm Signal... 186
Table A-1: Compartment geometry: 200
Table A-2: Compartment openings:... 200
Table A-3: Ventilation factors: 200
Table A-4: Time equivalence in minutes:.. 200
Table B-1: Geometry of compartments in CFAST model. 210
Table B-2: Material characteristics for compartment walls, ceilings and floors in CFAST. 211
Table B-3: Time for the smoke layer to reach z = 2.2 m in each control volume. ... 214
Table B-4: Times to reach 45°C for the lower layer and 200°C for the upper layer for each control volume 216
Table B-5: ASET corresponding to different tenability criteria obtained with CFAST 216
Table B-6: Material characteristics for compartment walls, ceilings and floors in FDS. 217
Table B-7: ASET corresponding to different tenability criteria obtained with CFAST 230
Table C-1: CF1 fire scenario characteristics. 234
Table C-2: CF1 fire scenario, RSET summary (manual calculations). 235
Table C-3: CF1 fire scenario, ASET zone model assumptions. 235
Table C-4: CF1 fire scenario, ASET summary (zone modeling). 236

Table C-5: RC1 fire scenario characteristics. 237
Table C-6: RC1 fire scenario, RSET summary (manual calculations). 237
Table C-7: RC1 fire scenario, ASET zone model assumptions. 237
Table C-8: RC1 fire scenario, ASET summary (zone modeling). 238
Table C-9: UT2 fire scenario characteristics. 242
Table C-10: UT2 fire scenario, RSET summary (manual calculations). 243
Table C-11: UT 2 fire scenario, ASET zone model assumptions. 243
Table C-12: UT2 fire scenario, ASET summary (zone modeling) 243
Table C-13: CF2 fire scenario characteristics. 244
Table C-14: CF2 fire scenario, RSET summary (manual calculations). 245
Table C-15: CF 2 fire scenario, ASET zone model assumptions. 245
Table C-16: CF2 fire scenario, ASET summary (zone modeling). 245
Table C-17: RC7 fire scenario characteristics. 247
Table C-18: RC7 fire scenario, RSET summary (manual calculations). 247
Table C-19: RC7 fire scenario, ASET summary (zone modeling). 248
Table C-20: UT1 fire scenario characteristics. 250
Table C-21: UT1 fire scenario, RSET summary (manual calculations). 251
Table C-22: UT 1 fire scenario, ASET zone model assumptions. 251
Table C-23: UT1 fire scenario, ASET summary (zone modeling). 252
Table C-24: CF3-CF5 fire scenario characteristics. 253
Table C-25: CF3-CF5 fire scenario, RSET summary (manual calculations). 254
Table C-26: CF 5 fire scenario, ASET zone model assumptions. 254
Table C-27: CF3 fire scenario, ASET summary (zone modeling). 255
Table C-28: CF4 fire scenario, ASET summary (zone modeling). 255
Table C-29: CF5 fire scenario, ASET summary (zone modeling). 256
Table C-30: RC4 fire scenario characteristics. 257
Table C-31: RC4 fire scenario, RSET summary (manual calculations). 258
Table C-32: RC 4 fire scenario, ASET zone model assumptions. 258
Table C-33: RC4 fire scenario, ASET summary (zone modeling) for design (a). ... 259
Table C-34: RC4 fire scenario, ASET summary (zone modeling) for design (b). ... 259
Table C-35: RC5 fire scenario characteristics. 260

Table C-36: RC5 fire scenario, RSET summary (manual calculations). 260
Table C-37: RC 5 fire scenario, ASET zone model assumptions. 261
Table C-38: RC5 fire scenario, ASET summary (zone modeling) for design (a). ... 261
Table C-39: RC5 fire scenario ASET summary (zone modeling) for design (b) 262
Table C-40: RC8 fire scenario characteristics. 262
Table C-41: RC8 fire scenario, RSET summary (manual calculations). 263
Table C-42: RC 8 fire scenario, ASET zone model assumptions. 263
Table C-43: RC8 fire scenario, ASET summary (zone modeling). 264
Table C-44: RC9 fire scenario characteristics. 264
Table C-45: RC9 fire scenario RSET summary (manual calculations). 265
Table C-46: RC 9 fire scenario, ASET zone model assumptions. 265
Table C-47: RC9 fire scenario ASET summary (zone modeling) 266
Table C-48: RC10 fire scenario characteristics. 266
Table C-49: RC10 fire scenario, RSET summary (manual calculations). 267
Table C-50: RC10 fire scenario, ASET zone model assumptions. 267
Table C-51: RC10 fire scenario, ASET summary (zone modeling). 268
Table C-52: Emitted heat fluxes from. 269
Table C-53: Time taken for initial Brigade notification 270
Table C-54: Dispatch time 271
Table C-55: Time taken for firefighters to respond dispatch call 271
Table C-56: Travel time 272

List of Figures

Figure 1-1: The fire design process as presented by C. Wade et al. [7]: Existing practice (left) and suggested approach (right). 5
Figure 2-1: Design process overview for the Verification Method 12
Figure 2-2: Idealized heat release rate history highlighting the four phases of conventional fire development and flashover. 27
Figure 3-1: Floor plan of car park basement levels, B1 & B2. 53
Figure 3-2: Floor plan of the ground floor 54
Figure 3-3: Floor plan of office floors, L1-L2. Half of the first floor consists of library, while the 6th and 7th floor are connected by an open internal staircase in the lower left corner. 55
Figure 3-4: Examples of evacuating floors according to the fire strategy, when a fire is detected in the building. 59
Figure 3-5: The floor plan shows 14 car park spaces. Up to 10 of these car parking spaces are located side by side. 65
Figure 3-6: Measured HRRs for five different burning medium sized cars (Reproduced from M. Z. M. Tohir's research [33]). 66
Figure 3-7: Placement of cars in experiment for fire spread between vehicles (Reproduced from M. Z. M. Tohir's research [33]). 67
Figure 3-8: Theoretical HRRs from Rotterdam Car Park investigation (Reproduced from Efectis Nederlands-report [35]). 68
Figure 3-9: Theoretical total HRRs from Rotterdam Car Park investigation (Reproduced from Efectis Nederlands-report [35]). 68
Figure 3-10: HRR evolution for a clerical workstation. Test 1 proposes the most severe HRR (Reproduced from SFPE Handbook [37]). 70
Figure 3-11: Placement of workstations during free burn experiment (Reproduced from S. Kakegawa's research [38]). 71
Figure 3-12: HHR for a burning 2-persons sofa (Test F32) (Reproduced from SFPE Handbook [37]). 72

Figure 3-13: HRRs for different types of stores (Reproduced from G. Hadjisophocleous' research [40]). 73
Figure 3-14: HRRs for free burning of open shelves (Reproduced from W. D. Walton's research [41]).......... 74
Figure 3-15: Illustration of design smoke layer depth (Reproduced from J. H. Klote's research [43]). 76
Figure 3-16: CFAST model of ground floor and smoke layer heights for different locations of the design fire at unspecified times. 85
Figure 3-17: Locations of design fires 86
Figure 3-18: HRR evolution for the design fire in the retail space. The constant peak HRR continues throughout the 700 s long simulation. 87
Figure 3-19: Evolution of fire area for the design fire. The peak area is 5 m^2. 88
Figure 3-20: Severity of fuel types. 88
Figure 3-21: Screenshot of Pathfinder Evacuation Model.......... 90
Figure 3-22: Evacuation times for the retail shops as dependent on exit widths. 91
Figure 3-23: Time evolutions of smoke layer height and temperatures. The dashed lines indicate performance criteria limits. 93
Figure 3-24: ASETs vs. RSETs for the small shop for each performance criterion. RSET_upper and RSET_lower indicate the RSETs for the upper and lower velocity fractiles, while the ASETs represent various growth rates. 94
Figure 3-25: ASET vs. RSETs for the small shop for the layer height criterion. RSET_upper and RSET_lower indicate the RSETs for the upper and lower velocity fractiles. The shown ASET is determined by the initial fire growth rate of 0.101 kW/s^2. 95
Figure 3-26: RSETs vs. ASET for varied occupant velocity and mean pre-movement time. Alpha = fire growth rate. SD = Standard Deviation. 96
Figure 3-27: RSETs vs. ASET for varied pre-movement time and mean occupant velocity. Alpha = fire growth rate. SD = Standard Deviation. 97
Figure 3-28: RSETs vs. ASETs for the different design fires in the office area. The RSETs (black lines) are based on various pre-movement times, while the ASETs

(colored lines) depend on the ceiling height. The occupants move with mean velocity. 99
Figure 3-29: CFAST model for a regular office floor. The smoke distribution at an unspecified time is shown to the right. Doors are assumed open. 100
Figure 3-30: HRR evolutions for the different fuel types on the office floors. 102
Figure 3-31: Screenshot of FDS model. 104
Figure 3-32: HRR output produced by FDS. 104
Figure 3-33: Smoke evolution in the FDS office model, seen from the top. 105
Figure 3-34: Smoke evolution in the FDS office model, seen form the side............ 106
Figure 3-35: Screenshots of Pathfinder Evacuation Model, office floors. 108
Figure 3-36: Evacuation time as dependent on the exit widths for the office area... 109
Figure 3-37: Time evolutions of smoke layer height and temperatures for the sofa fire scenario. The dashed lines indicate performance criteria limits. 111
Figure 3-38: RSETs vs. ASETs for the different design fire scenarios. The RSETs (black lines) are based on various pre-movement times, while the ASETs (colored lines) depend on the ceiling height. 112
Figure 3-39: Layer height evolution in the staircase, when the ceiling height is 3.1 m. The FDS outcomes are spatially distributed, so the mean layer height and the mean layer height plus two standard deviations are specified... 113
Figure 3-40: Layer height evolution in the staircase, when the ceiling height is 2.9 m. The FDS outcomes are spatially distributed, so the mean layer height and the mean layer height plus two standard deviations are specified... 114
Figure 3-41: CFAST model of one basement level. The vehicle ramp is modeled as an opening. All doors between the parking area and the staircase are assumed open... 115
Figure 3-42: HRR evolution for a vehicle design fire. 115
Figure 3-43: Evolution of fire area for the vehicle design fire. The peak area is 6 m^2 and is reached faster than the peak HRR. 116
Figure 3-44: Screenshot of Pathfinder Basement Model. 117
Figure 3-45: Evacuation times as dependent on exit widths. The safety compartment is the compartment between the parking area and the staircase. 118

Figure 3-46: Time evolutions of smoke layer height and temperatures. The dashed lines indicate performance criteria limits. 120
Figure 3-47: RSETs vs. ASETs for the different areas on in the basement. The RSETs (Black lines) are based on various occupant velocities, while the ASETs (Colored lines) depend on fire growth rate. Alpha = Fire growth rate. SD = Standard deviation. 121
Figure 3-48: Floor plan of basement. 123
Figure 3-49: Floor plan of ground floor. Exit widths are shown. 124
Figure 3-50: Floor plan of regular office area. 125
Figure 5-1: Example of fire heat release rate (HRR) and fire area growth implementation into CFAST (CF 2 fire scenario – Challenging fire in retail area) . 161
Figure 5-2: Location of design fire in the BE1 scenario. 162
Figure 5-3: Location of design fire in the UT1 scenario. The fire occurs in a storage room. 162
Figure 5-4: Location of design fire in the UT2 scenario. The fire occurs in a storage room. 164
Figure 5-5: Location of design fire in the CS1 scenario.The fire occurs in the ceiling space. 165
Figure 5-6: Location of design fire in the CF1 scenario in the basement. 167
Figure 5-7: Location of the design fire in the CF2 scenario on the ground floor. 168
Figure 5-8: Location of design fire in the CF3, CF4 & CF5 scenarios on the office floors. 170
Figure A-1: Maximum temperature concept (Reproduced from Structural Design for Fire safety [18]). 201
Figure A-2: Effect of cooling phase (Reproduced from S. E. Magnusson & S. Thelandersson's work [66]). 203
Figure B-1: Geometry of CFAST model. 210
Figure B-2: HRR evolution in CFAST model. 211
Figure B-3: Fire area evolution in CFAST model. 212
Figure B-4: Evolution of smoke layer at specified times. Left: Upper layer temperature. Right: Smoke visualization 213

Figure B-5: Evolution of smoke layer height for each control volume in CFAST... 214
Figure B-6: Evolution of lower layer temperature for each control volume. 215
Figure B-7: Evolution of upper layer temperature for each control volume. 215
Figure B-8: Screenshots of FDS model. 217
Figure B-9: Illustration of grid size in FDS. 218
Figure B-10: HRR input for FDS... 219
Figure B-11: Heat Release Rate input in FDS (red line) and output (black line). 220
Figure B-12: Evolution of the smoke layer in the retail space for times 25, 50, 70, 90, 120 and 150 s. 221
Figure B-13: Layer height evolution... 222
Figure B-14: Lower layer temperature evolution. 223
Figure B-15: Upper layer temperature evolution. 223
Figure B-16: Temperature profiles for compartment 2 and 3 calculated from thermocouple trees. The black dashed lines indicate the size boundaries for the cell that the CFAST values lie within. 226
Figure B-17: Temperature profiles at t = 30 s... 227
Figure B-18: Temperature profiles at t = 88 s... 228
Figure B-19: Temperature profiles at t = 140 s... 229
Figure C-1: Location of design fire on the B2 level in the CF1 scenario. 234
Figure C-2: CFAST model at the time ASET is reached for the B2 floor............... 235
Figure C-3: Location of design fire on the B2 level in the RC1 scenario. 236
Figure C-4: CFAST model at the time ASET is reached for the RC1 scenario. 238
Figure C-5: Location of the design fire in the BE2 scenario. 241
Figure C-6: Location of the design fire in the UT2 scenario. The fire is located in a storage room... 242
Figure C-7: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right. 243
Figure C-8: Location of design fire on the ground floor in the CF2 scenario. 244
Figure C-9: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right. 245
Figure C-10: Location of the design fire on the ground floor in the RC7 scenario. . 246

Figure C-11: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right. 247
Figure C-12: Location of the design fire on the office floor in the BE1 scenario. ... 249
Figure C-13: Location of the design fire on the office floor in the UT1 scenario. The fire is located in a storage room. 250
Figure C-14: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right. 251
Figure C-15: Location of the design fire on the office floor in the CF scenarios. 253
Figure C-16: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right. 254
Figure C-17: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right. 255
Figure C-18: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right. 256
Figure C-19: Location of design fire on the office floor for the RC3 – RC5 scenarios. 257
Figure C-20: CFAST model at the time ASET is reached for design (a) 258
Figure C-21: CFAST model at the time ASET is reached for design (b). 259
Figure C-22: CFAST model at the time ASET is reached for design (a). 261
Figure C-23: CFAST model at the time ASET is reached for design (b). 262
Figure C-24: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right. 263
Figure C-25: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right. 265
Figure C-26: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right. 267
Figure C-27: View factor diagram. 269
Figure E-1: CF 2 zone model geometry 279
Figure E-2: CF 2 fire heat release rate (HRR) and fire area growth implementation into CFAST. 280
Figure E-3: CF 2 zone model at 95 s 280

Figure E-4: CF 2 smoke layer height for different control volumes........................ 281
Figure E-5: CF 2 gas-phase temperature at 2 m above egress paths for different control volumes.. 281
Figure E-6: CF 2 $FED_{thermal}$ at 2 m above egress paths for different control volumes 282
Figure E-7: CF 2 visibility at 2 m above egress paths for different control volumes 282

List of Abbreviations

ABCB	Australian Building Codes Board
ADB	Approved Document B, Vol. 2
AFAC	Australasian Fire and Emergency Service Authorities Council
AS	Standards Australia
ASET	Available Safe Egress Time [s]
AU	Australia
B1-B2	Basement Level 1 & 2
BCA	Building Code of Australia
CFD	Computational Fluid Dynamics
C/VM2	The New Zealand Building Code Verification Method VM2
DtS	Deemed-to-Satisfy
FBIM	Fire Brigade Intervention Model
FDS	Fire Dynamics Simulator
FED	Fractional Effective Dose
FPA	Fire Protection Association Australia
FRL	Fire Resistance Level
HRR	Heat Release Rate
ICC	International Code Council
IFEG	International Fire Engineering Guidelines 2005
ISO	International Organization for Standardization
L1-L7	Floor levels 1 through 7
MFB	Metropolitan Fire Brigade
NCC	National Construction Code
NFPA	National Fire Protection Association
PBD	Performance-Based Design

PBDB	Performance-Based Design Brief
RRFS	Regulatory Reform (Fire Safety) Order 2005
RSET	Required Safe Egress Time [s]
SD	Standard Deviation
SFPE	Society of Fire Protection Engineers
UK	United Kingdom
UQ	University of Queensland
VAS	Voice Alarm Signal
VM	Verification Method

Chapter 1 Introduction

Since the beginning of the 20th century, prescriptive codes have been used in specifying fire protection systems in buildings [1], while the concepts of performance-based regulations and engineered approaches to building fire safety weren't introduced until the 1970s [2].

When a building is to be designed for fire safety today, one of the main design tools utilized around the world is the application of prescriptive building codes. The prescriptive codes prescribe sets of measures to reach fire safety in enclosures and are commonly referred to as "Deemed-To-Satisfy" (DtS) solutions, which provide a minimum acceptable level of fire safety. The implication is that the correct application of prescriptive codes implicitly delivers the minimum acceptable level of safety.

The first step when designing a building using the prescriptive approach is to determine the occupancy classification(s) of the building. The codes will then identify the requirements for the given occupancy classification, which can be directly interpreted, allowing for a fast design process. Furthermore, the ongoing enforcement of the codes is eased in that most building in the same occupancy classification will have the same features [3].

However, prescriptive codes have evolved over many decades, which have resulted in them becoming more complex and often difficult to use for new technologies and change in practices, inhibiting innovation [1]. Also, although the prescriptive codes specify detailed requirements for the achievement of fire safety, they do not explain exactly how to reach this level of safety as no clear guidance on how to develop and assure it is provided. Consequently, the costs of fire designs based on prescriptive codes tend to be high, and the life safety of the occupants cannot be guaranteed [4].

In recent decades, many building codes, regulations and standards have been going through a transition from prescriptive-based to performance-based [1]. Performance-Based Design (PBD) has become more common as buildings have increased in complexity. The SFPE Engineering Guide to Performance-Based Fire Protection [5] defines performance-based design as "an engineering approach to fire protection design based on agreed upon fire safety goals and objectives, deterministic and/or probabilistic analysis of fire scenarios and quantitative assessment of design alternatives against the fire safety goals and objectives using accepted engineering tools, methodologies and performance criteria." The performance-based design approach allows the engineer to describe the desired level of fire safety in the building in the event of a fire as well as to define the preferred design basis. The engineer will then have to perform an engineering analysis in order to demonstrate that the proposed design strategies provide the intended level of safety for the building.

The advantages of PBD and performance-based codes are potentially significant [1]. These include the cost-effectiveness and flexibility in design and the capability to use innovative solutions and new technologies and knowledge as it becomes available, while also promoting better understanding of a building's performance in the event of a fire. Among the disadvantages that follow is the high level of expertise required by the designer, and the fact that a PBD process requires more time to conduct and review than a prescriptive-based design procedure. Also, a performance-based designed building is sensitive to change in design as it can lead to unacceptable performance [6].

The definition of the performance criteria is highly regarded as one of the main challenges in a PBD process [1]. The current PBD framework as well as performance-based codes lead to significant variability in the design fire scenarios and performance criteria [7]. While one designer might evaluate tenability criteria at 1.8 m above the floor, another designer may choose to calculate them at 2.0 m above the floor. These irregularities arise from the lack of a clear process from the regulators for performance criteria, design fire characteristics and scenarios when using a PBD approach. In order to avoid arbitrariness and variation in quality when determining the level of fire safety for performance-based design, it has been argued that a regulatory process is needed.

Such regulatory process can be provided by a verification test method. A verification method is intended a tool to verify that the performance has been met of a building that is already designed as an acceptable or a performance solution. The proposed design is taken through the process of verification, on a systems and more detailed level, to ensure that the criteria for acceptance have been met [8]. A series of verification tasks, with each one addressing one or more requirements, must be completed and passed. The typical methods to conduct these verification tasks include analysis techniques, mathematical modeling and laboratory tests.

In 2016, Verification Methods were introduced in Australia’s National Construction Code (NCC) for structural engineering, and the Australian Building Codes Board

(ABCB) has produced a Handbook for Structural Robustness [9] which provides support in understanding these Verification Methods and the structural robustness requirements of the NCC. The handbook defines a VM as “A test, inspection, calculation or other method that determines whether a Performance Solution complies with the relevant Performance Requirements.” The NCC Verification Methods propose a way to demonstrate compliance with some of the structural performance requirements defined in the NCC, however, without quantifying them. These VMs are merely tests to be carried out after a performance solution has been developed, without interfering with the PBD process itself. The VM is thus a layer being applied after a performance solution already has been completed as a means to verify that the performance design solution complies with the performance requirements of the NCC.

1.1 Verification Method 2 in New Zealand

Performance-based buildings codes in New Zealand were introduced in 1991 [10], but in 2013 New Zealand introduced a new method to demonstrate compliance with the New Zealand Building Code: Verification Method 2: Framework for Fire Safety Design (C/VM2) [11] [13]. This method suggested a different approach than the existing PBD practice, as visualized on Figure 1-1. The C/VM2 undertook the challenge of specifying the performance criteria, design fires and scenarios, which in the existing framework was the fire engineer’s job. Thereby, the Verification Method appeared to be a design method that worked as a compromise between prescriptive methods and performance-based design, substituting the role of the designer in certain areas of the design process.

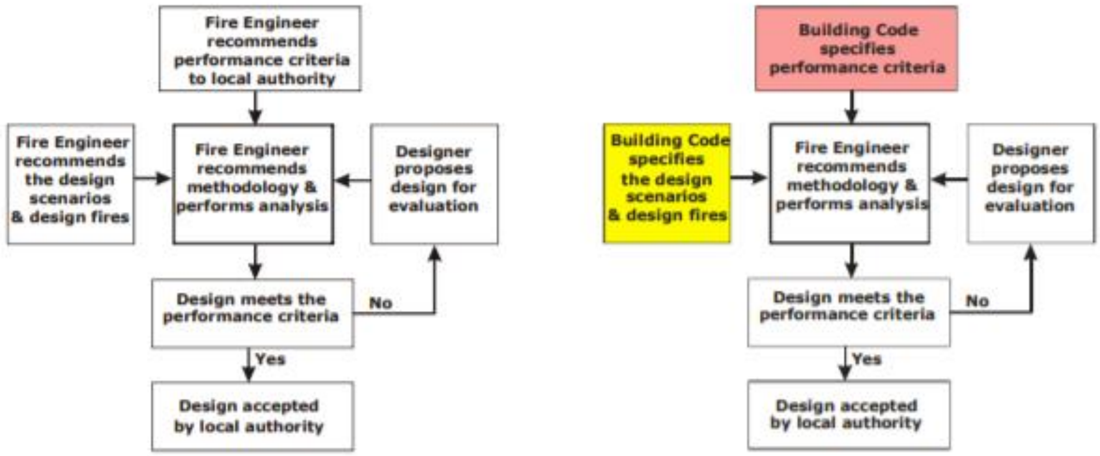


Figure 1-1: The fire design process as presented by C. Wade et al. [7]: Existing practice (left) and suggested approach (right).

The quantification of the performance criteria sets the C/VM2 apart from the VMs available in the NCC for structural robustness. While the NCC VMs are merely methodologies intended to verify a design's compliance with performance requirements established in the prescriptive codes, the C/VM2 transforms into a design methodology as it interferes with the PBD process by specifying the performance criteria for the designer. As a result, the C/VM2 is significantly longer and more comprehensive than the NCC VMs.

The C/VM2 lists ten prescriptive design scenarios to be considered and modeled, while also defining parameters such as design fire inputs, human characteristics, radiation limits etc. The designer must decide the locations of the design fires and which design scenarios that are relevant to the given building. Moreover, the Verification Method prescribes performance criteria that are universal to all buildings complying with the C/VM2. Alternation of some of the prescribed values is allowed, but requires technical argumentation by the designer.

The C/VM2 method provides a much more consistent framework for analyzing performance of buildings, thereby reducing the uncertainty in the design process. Prior to the introduction of the C/VM2, a large amount of time was spent on defining the performance criteria and design inputs, but as this time was significantly reduced, more time could be spend on the design process itself [14]. On the other hand, the C/VM2 stifles creativity and can lead to over and under design. As exemplified by M. James, there is no option to reduce the few available prescribed fuel loads and design fires sizes, although these large fires cannot be supported in some spaces such as small rooms [14]. Furthermore, it doesn't obligate the designer to consider any other design scenarios than those listed in the C/VM2, despite the probability that more complex buildings may require design scenarios that address uncommon fire safety concerns. The C/VM2's lack of guidance in certain areas such as vertical smoke movement within a building must also be noted [14]. Moreover, Meacham (2017) points out that there is a perceived shortage of adequately qualified and competent fire engineers in New Zealand, while at the same time it is expected that the C/VM2 is only to be used by qualified and competent engineers (whose absence was the original motivation). The issue is that there is a clear lack of enforced, minimum competency and qualifications criteria for use in determining which engineers have the appropriate knowledge, expertise and skill set to carry out fire solutions that are not prescriptive. This applies to both the performance-based design and methods such as the C/VM2 [12].

1.2 Fire Safety Approaches in Australia, USA and UK

1.2.1 Australia

Fire safety design in Australia was largely based on compliance with the prescriptive or Deemed-To-Satisfy requirements of the Building Code of Australia (BCA) up until 1997 [15], when the prescriptive regulatory structure was replaced with a performance-based format. The performance-based BCA still provides prescriptive guidance while allowing for a performance-based approach to fire safety. The BCA sets out objectives and functional statements that in general terms express guidance on how to interpret the content and intent of the Performance Requirements and the DtS provisions [21].

A building design must meet all the relevant Performance Requirements in order to receive regulatory approval. In order to comply with the Performance Requirements, a building solution may be:

- A design that complies with the Deemed-to-Satisfy Provisions;
- An alternative solution;
- A combination of both.

In Australia, the intention of the prescriptive building regulations is to mitigate risks to a level tolerated by the community. The performance requirements reflect a benchmark with respect to the risk of fatality, injury and loss of adjacent structures through fire, but it is not intended to be a "zero risk" benchmark. Instead, they reflect the expectation of and cost to the community. The alternative solution is not a prescribed DtS solution, but does instead open up for the opportunity to show compliance with the performance requirements through analysis. An issue of the alternative solution is the lack of quantification of the Performance Requirements in the BCA, and that the level of safety provided by the BCA is not explicitly stated. This leads to uncertainties when interpreting the performance requirements as the interpretation of these depends on engineering judgment, which can vary between individual practitioners [21].

The ABCB wishes to adopt a modified version of the Verification Method developed by New Zealand. The Verification Method (VM) is to be implemented in the National Construction Code (NCC) 2019. For this purpose, the Fire Protection Association Australia (FPA Australia) has been awarded the task of completing a calibration study for the proposed ABCB Verification Method. In the calibration study, six buildings that are compliant to the BCA's Deemed-to-Satisfy requirements have been assessed against the proposed Verification Method.

1.2.2 USA

The United States does not have a single nation-wide building code. The fire regulations in USA is drafted and enforced by private organizations and not the US Federal Government. These organizations include the International Code Council (ICC) and the National Fire Protection Association (NFPA). Both organizations have both performance-based and prescriptive codes available, but while the ICC has published a stand-alone performance-based code titled "The ICCC Performance Code for Buildings and Facilities," the NFPA has incorporated a performance-based design option within NFPA 5000. However, both approaches mainly support the use of prescriptive documents as the primary available solutions [22].

1.2.3 United Kingdom

In 1985, the UK moved from a largely prescriptive and rather restrictive approach to more flexible and intelligent systems in the building regulations. This reform meant that the building regulations were reduced from 307 pages to only 23 pages. Acceptance criteria and methods were not included in the new building regulations, which meant that the engineers had the opportunity to choose their own performance criteria, safety factors, engineering methods and verification methods to demonstrate compliance [23]. However, because of the complexity in gaining acceptance for methods that not everybody agrees on, many designers and engineers choose to rely on the prescriptive guidance provided in the "Approved Documents" and a series of British Standards (BS 5588 series), issued as Deemed-to-Satisfy solutions.

The Approved Document B offers guidance on fire safety requirements, which are only meant as recommended guidelines. If full compliance with the Approved Documents isn't possible, an alternative approach of fire engineering is allowed and can be used to develop alternative ways of achieving compliance with the intent of the requirements.

1.3 Objective of Research

As the Verification Method approach becomes more widespread as a design tool option, there is a need for a critique of the concepts behind the method. This critique will highlight advantages and weaknesses of the method by using examples from a case study which will be conducted in order to scrutinize the design process of the Verification Method as well as its defined parameters. The examples will cover assumptions for modeling, chosen methodologies, flexibility, decision making and level of expertise required of the designer. In conclusion, a final assessment of the concept of the Verification Method as a design tool will be established.

The case study that will be explored in depth is a high-rise building, consisting of mixed occupancies, namely office spaces, retail areas and a car parking basement. The choice of a small high-rise building was made on the basis that it is a simple enough problem so it should be an easy target for the Verification Method approach, but it also incorporates some of the complexities that highlight the potential value of the methodology. Various design examples of the high-rise building will be developed based upon a performance-based design method, prescriptive codes from Australia, USA and the United Kingdom, and finally using the proposed Verification Method. The performance-based design will not be based on any performance-based codes and will serve as an example of the ideal design solution of the case building, while the prescriptive designs will serve as benchmarks for an acceptable solution. The final building design outcomes and the methods utilized in the different design approaches will then be assessed against each other. The main focus of fire safety in this project is life safety of occupants.

1.4 Report overview

Following the introduction, chapter 2 describes and explains the existing Verification Method from Australia in details. Chapter 3 contains the performance-based design of the building, which will also include an elaborate description of the structure and its occupancies. In chapter 4, three prescriptive codes will be applied to the building. These codes are the BCA from Australia, NFPA 101 from USA and Approved Document B from the UK. A comparison of the three outcomes and the PBD will follow the application of the codes. The application of the Verification Method design is provided in chapter 5. Results and examples from the processes in the previous chapters will be used to make up chapter 6, which represents the outcomes of the various designs and the critique of the Verification Method. The examples will be used to illustrate perceived advantages and observed weaknesses of the VM as a design tool, before the paper is terminated with a conclusion.

Chapter 2 Summary of Existing Fire Safety Verification Method

2.1 Introduction

In Australia, the Verification Method (VM) is one way to demonstrate compliance with the performance requirements of the BCA. A building must be assessed against 12 design scenarios that are specified by the VM. The design scenarios are developed in such a way that they cover the performance requirements of the BCA, thereby addressing elements that are currently regulated by the BCA. Some of the scenarios require simple solutions, such as simple heat flux calculations, while others entail detailed analysis. For these scenarios, design fires must be applied, which the VM also prescribes for the designer.

The design process for the BCA Fire Safety Verification Method is shown in Figure 2-1. Firstly, a Performance-Based Design Brief (PBDB) must be completed. This PBDB must include the scope of the project, relevant performance requirements, and the determination of relevant design scenarios, their rules and parameters. All decisions and assumptions must be included in the PBDB. Secondly, analysis of the defined design scenarios in the PBDB must be carried out. When the analysis has been conducted, the results must be evaluated. If the trial designs meet the acceptance criteria set by the PBDB, a final report can be prepared.

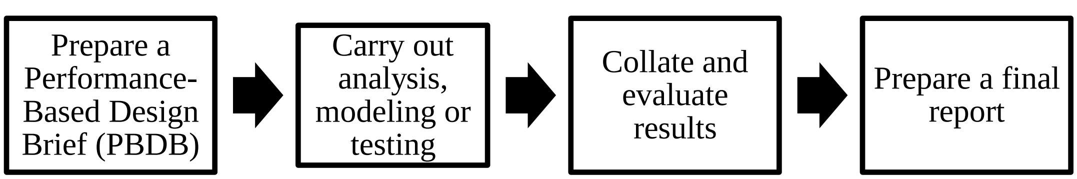


Figure 2-1: Design process overview for the Verification Method

The VM prescribes design fire inputs (fire growth rate, HRR etc.) and human characteristics (velocity, pre-movement time etc.), but it does not presume any particular methodologies for calculating the Available Safe Egress time (fire modeling) and the Required Safe Egress Time (evacuation modeling). The choice of fire and egress model is up to the engineer who must defend the methodologies utilized in the analysis.

In the subsequent sections, the occupant characteristics, design fires and design scenarios will be summarized.

2.2 Occupant Characteristics

This section of the VM deals with occupant types and numbers and calculating the RSET (Required Safe Egress Time) vs. ASET (Available Safe Egress Time). It is not the intention of the VM to provide a comprehensive guide to egress analysis, but rather to describe the minimum level of thoroughness expected in the egress calculations. This is in line with the general purpose of the VM outlined in its introduction.

2.2.1 Occupant Number and Design Occupant

The occupant densities are provided in BCA Table D1.13 (shown in Table 2-1) unless a more appropriate means is available.

Type of use		m^2 per person
Art gallery, exhibition area, museum		4
Bar	- Bar standing - Other	0.5 1
Board room		2
Boarding house		15
Café, church, dining room		1
Car park		30
Computer room		25
Court room	- Judicial area - Public seating	10 1
Dance floor		0.5
Dormitory		5
Early childhood center		4
Factory	(a) Machine shop, fitting shop or like place for cutting, for cutting, grading, finishing or fitting of metals or glass, except in the fabrication of structural steelwork or manufacture of vehicles or bulky products	5
	(b) Areas used for fabrication and processing other than those in (a)	50
	(c) A space in which the layout and natural use of fixed plant or equipment determines the number of persons who will occupy the space during working hourse	Area per person determined by the use of the plant or equipment
Gymnasium		3
Hostel, hotel, motel, guest house		15
Indoor sports stadium-arena		10
Kiosk		1
Kitchen, laboratory, laundry		10
Library	- Reading space - Storage space	2 30
Office, including one for typewriting or document copying		10
Patient care areas		10

Type of use		**m^2 per person**
Plant room	- Ventilation, electrical or other service units	30
	- Boilers or power plant	50
Reading room		2
Restaurant		1
School	- General classroom	2
	- Multi-purpose hall	1
	- Staff room	10
	- Trade and practical area (primary)	4
	- Trade and practical area (secondary)	As for workshop
Shop	- Space for sale of goods at a level entered direct from the open air or any lower level	3
	- Space for sale of goods at all other levels	5
Showroom	- Display area, covered mall or arcade	5
Skating rink, based on rink area		1.5
Spectator stand, audience viewing area:	- Standing viewing area	0.3
	- Removable seating	1
	- Fixed seating	Number of seats
	- Bench seating	450 mm/person
Storage space		30
Swimming pool, based on pool area		1.5
Switch room, transformer room		30
Telephone exchange (private)		30
Theatre and public hall		1
Theatre dressing room		4
Transport terminal		2
Workshop	- For maintenance staff	30
	- For manufacturing processes	As for factory

Table 2-1: Occupant Densities used in the VM, taken from BCA Table D1.13.

The occupants are divided into three different occupant type categories: Type A, B and C. The occupant type depends on potential activity limitations of the occupant, such as hearing impairment, vision impairment and mobility impairment, and the severity of this limitation. The type also depends on whether the occupant is awake or sleeping and familiar or unfamiliar with the building. The final occupant type is determined from Table 2-2.

	Mobility		**Hearing**		**Vision**	
Critical state	N	S/P	N	S/P	N	S/P
Awake and familiar with the building	A	C	A	B	A	B
Awake but unfamiliar	B	C	A	B	B	C
Likely to be asleep	B	C	B	C	B	C

Table 2-2: Occupant types, N = No impairment, S/P = Severe, profound impairment.

For type C occupants, the occupant characteristics listed in Table 2-3 will be used.

Characteristic	**Mobility**	**Hearing**	**Vision**
Vertical travel speed using stair (m/s)	0	Refer to section 2.2.2.	0.71
Horizontal travel speed (m/s)	0.69	1.2	0.86
Occupant density:	Stationary: $0.8925m^2$ (1216 x 813mm) 180 degree turn $3.18m^2$ (1540 mm x 2070 mm).	Refer to section 2.2.2.	Refer to section 2.2.2.
Notification time (recognition)	Refer to section 2.2.2.	Appropriate to available cue. i.e. Refer to section 2.2.2.	Refer to section 2.2.2.
Pre-travel time (subject to 2.2.2.3):	900 s* (when sleeping and unfamiliar)	Assume occupant is remote from compartment of origin.	900 s* (when sleeping and unfamiliar)
FED:	0.1	0.1	0.1

Table 2-3: Type C occupant characteristics.
*Note: * where the occupants are considered sleeping and under the care of trained staff (e.g. hospitals and rest homes), use values in section 2.2.2.*

For type A and B occupants, the occupant characteristics are determined from a wider range of assumptions which will be covered in the subsequent sections.

2.2.2 RSET

In the VM, the RSET can be calculated using special purpose egress computer models or simple hand calculations. The general RSET according to the VM is defined as:

$$RSET = (t_d + t_n + t_{pre}) + (t_{trav} + t_{flow}) \quad (2.1)$$

Where:

$t_d =$ Detection time determined from deterministic modeling.

$t_n =$ Time from detection to notification of occupants.

$t_{pre} =$ Time from notification until evacuation begins.

$t_{trav} =$ Time spent moving toward a place of safety.

$t_{flow} =$ Time spent in congestion controlled by flow characteristics.

As a simplification, the occupants are assumed to be evenly distributed in the given space.

2.2.2.1 Detection Time

The calculation of the detection time depends on whether the occupant warning system is manually or automatically activated. In the VM, manual activation of a warning system is only permitted in a space if:

(a) The average ceiling height is equal to or higher than 5 m;

(b) The occupants are awake and familiar with their surroundings;

(c) The occupant density calculations result in an occupant load of fewer than 50 persons.

In any other case, automatic detection must be considered. For a manually activated occupant warning system, the detection time is equal to the time it takes for the ceiling jet to completely traverse the entire length of the space from the fire at the opposite end of the space. Therefore, the detection time must be calculated as indicated in Table 2-4.

Storage height	**Dimension rates**	**Detection time**
Storage height ≤ 5 m (Ultrafast fire growth)	L ≤ 1.4w	$t_d = 10 + 2.4L$
	1.4w < L ≤ 4w	$t_d = 10 + w + 1.7L$
Storage height > 5 m (rack growth)	L ≤ 1.4w	$t_d = 25 + 1.7L$
	1.4w < L ≤ 4w	$t_d = 25 + w + L$

Table 2-4: Detection times for manually activated detection systems.
Notes: w = width of space in meters (shortest dimension), L = length of space in meters (longest dimension).

For automatic detection systems, the detection time shall be established from deterministic modeling. The VM doesn’t specify an explicit model, but allows:

(a) An appropriate algorithm that might include a ceiling jet correlation;

(b) A CFD model code that solves for the velocity and temperature (and smoke/soot concentration) directly;

(c) A simplified approach based on the depth of the hot gas layer where the occupants are assumed to be aware of the fire in the same room when the smoke Is below 5% of the ceiling height.

Although the VM doesn’t dictate a specific method to calculate the detection time, it does provide explicit values for the detector criteria that may be used in the analysis. These values are given in Table 2-5.

Heat detectors	Extended coverage (sprinkler)
RTI = 30 $m^{½}s^{½}$ T_{act} = 57°C Radial distance = 4.2 m Distance below ceiling not less than 25 mm	*RTI* = 50 $m^{½}s^{½}$ C = 0.65 $m^{½}s^{½}$ T_{act} = 68°C Radial distance = 4.3 m (maximum) Distance below ceiling not less than 25 mm
Standard response (sprinkler)	**Quick response (sprinkler)**
RTI = 135 $m^{½}s^{½}$ C = 0.85 $m^{½}$ $s^{½}$ T_{act} = 68°C Radial distance = 3.25 m Distance below ceiling not less than 25 mm	*RTI* = 50 $m^{½}$ $s^{½}$ C = 0.65 $m^{½}$ $s^{½}$ T_{act} = 68°C Radial distance = 3.25 m Distance below ceiling not less than 25 mm
Spot/point smoke detectors	**Projected beam smoke detectors**
Optical density at alarm = 0.14 m^{-1} Radial distance = 7 m Distance below ceiling not less than 25 mm	Optical density at alarm to be determined based on beam path length and the design setting for the total obscuration for alarm

Table 2-5: Detector criteria defined by the VM.

2.2.2.2 Notification Time

According to the VM, the notification time may be assumed as 20-40 seconds for type A occupants. If vibro/tactile and ISO 8201 T3 520 Hz alarm signals are used, the notification time may also be assumed as 20-40 seconds for type C hearing impaired occupants who are asleep and unfamiliar with the building. However, no notification time is specified in the VM for type B occupants, the remaining type C occupants and buildings without suitable alarm systems. Instead, it is stated that extended notification time is required.

2.2.2.3 Pre-movement Activity Time

The values for pre-movement activity time are clearly stated in the VM, although it is pointed out that the lack of consideration of the incipient phase of the fire growth in the design fire should be made up for an unknown safety factor for the pre-movement activity time. The pre-movement activity times are provided in Table 2-6 below.

Description of building use	Pre-travel activity time(s)
Buildings where the occupants are awake, alert and familiar with the building (e.g. offices, warehouses not open to the public)	
Enclosure of origin	30
Remote from the enclosure of origin	60
Buildings where the occupants are awake, alert and unfamiliar with the building (e.g. retail shops, exhibition spaces, restaurants)	
Enclosure of origin (standard alarm signal)	60
Remote from the enclosure of origin (standard alarm signal)	120
Enclosure of origin (voice alarm signal)	30
Remote from the enclosure of origin (voice alarm signal)	60
Buildings where the occupants are sleeping and familiar with the building (e.g. apartments)	
Enclosure of origin (standard alarm signal)	60
Remote from the enclosure of origin (standard alarm signal)	300

Description of building use	Pre-travel activity time(s)
Buildings where the occupants are sleeping and unfamiliar with the building (e.g. hotels and motels)	
Enclosure of origin (standard alarm signal)	60
Remote from the enclosure of origin (standard alarm signal)	600
Remote from the enclosure of origin (voice alarm signal)	300
Buildings where the occupants are awake and under the care of trained staff (e.g. day care, dental office, clinic)	
Enclosure of origin (independent of alarm signal)	60
Remote from the enclosure of origin (independent of alarm signal)	120
Buildings where the occupants are sleeping and under the care of trained staff (e.g. hospitals and rest homes)	
Enclosure of origin (assume staff will respond to room of origin first)	60 s for staff to respond to alarm then 120 s (per patient per 2 staff)[1]
Remote from the enclosure of origin (independent of alarm signal)	1800
Remote from the enclosure of origin (independent of alarm signal) where occupants are unable to be moved due to the procedure or other factor	1800 or as per specific requirements, whichever is the greater
Spaces within buildings which have only focused activities (e.g. cinemas, theatres and stadiums)	
Space of origin (occupants assumed to start evacuation travel immediately after detection and notification time or when fire in their space reaches 500 kW, whichever occurs first)	0

Description of building use	Pre-travel activity time(s)
NOTE: 1. This allows 120 s to move each patient from their room to the next adjacent fire compartment. This includes time for staff to prepare the patient and transport them to the adjacent fire compartment, and then to return to evacuate another patient.	

Table 2-6: Pre-movement activity times as defined in the VM.

2.2.2.4 Travel time

The evacuation time within a space is equal to the greatest of:

(a) The time taken to travel to an exit, t_{trav};

(b) The flow time, t_{flow}, which is the time taken for all occupants in the space to flow through a restriction such as a doorway or a narrowing corridor when queuing is necessary.

The travel speed for type A and B occupants is calculated by using equation:

$$S = k - akD \qquad (2.2)$$

Where:

S = Travel speed (m/s)

D = Occupant density of the space (persons/m^2)

a = 0.266

k = Constant depending on horizontal/vertical travel. See Table 2-7.

Exit route elements		k	Speed m/s
Corridor, aisle, ramp, doorway		1.40	1.19
Stair riser (mm)	Stair tread (mm)		
191	254	1.00	0.85
178	279	1.08	0.95
165	305	1.16	1.00
165	330	1.23	1.05

Table 2-7: Maximum speeds for vertical travel for type A and B occupants.

For type C occupants, the travel speed is given in Table 2-3.

The travel time is calculated by using equation:

$$t_{trav} = \frac{L_{trav}}{S} \tag{2.3}$$

Where

t_{trav} = Travel time (s)

L_{trav} = Travel distance (m)

The VM doesn't address how to measure the travel distance for vertical travel, while for horizontal travel the maximum travel distance is specified as:

(a) The measured length around furniture if this is known;

(b) Adding together the length and width measurements of the room.

2.2.2.5 Flow time

Both hand calculations and computational techniques can be used to determine the flow time. If hand calculations are used, the flow rate must be calculated using equation:

$$F_c = (1 - aD)kDW_e \tag{2.4}$$

Where:

F_c = Calculated flow (persons/sec).

D = Occupant density near flow constriction (i.e. for doors use 1.9 persons/m^2 – See Table 2-3 for type C occupants).

W_e = Effective width of component being traversed in meters.

The effective width is equal to the measured width minus the boundary layer for which the thickness is given in Table 2-8.

Exit route element	Boundary layer on each side (m)
Stairway – walls or side tread	0.15
Railing or handrail	0.09
Theatre chairs, stadium bench	0.00
Corridor wall and ramp wall	0.20
Obstacle	0.10
Wide concourse, passageway	0.46
Door, archway	0.15

Table 2-8: Boundary layer width of exit components.

If a door leaf is fitted with a self-closing device (not including automatic sliding doors), the maximum flow rate through that door leaf is maximum 50 persons/min. This maximum flow rate corresponds to a 0.95 m wide door for type A and type B occupants. If the door is not fitted with a self-closing device, there is no upper limit on the flow rate, thus making equation 2.4 limitless.

2.2.2.6 Direction of Opening

Doors on all escape routes must comply with BCA clause D2.20 about swinging doors, which states that a swinging door:

(a) Must not encroach at any part of its swing by more than 500 mm on the required width, including any landings, of a required stairway, ramp or passageway if it is likely to obstruct the path of travel of the people already using the exit;

(b) Must not encroach when fully open, by more than 100 mm on the required width of the required exit (Measurement of encroachment includes door handles or other furniture or attachments to the door);

(c) Must swing in the direction of egress unless:

- The door serves a space of not more than 200 m^2 from where it is the only required exit and it is fitted with a device for holding it in the open position.
- The door serves a sanitary compartment of airlock.

(d) Must not otherwise impede the path or direction of egress.

2.2.3 Requirements for Delayed Evacuation Strategies

When a delayed evacuation (phased evacuation) strategy is used within any part of a building so that occupants are to stay in a safe place inside the building, such safe space appropriate to the occupant density must be contained within the building.

2.2.4 Fire Modeling to determine ASET

For some of the design scenarios it is required that the designer must demonstrate that the occupants have sufficient time to evacuate the building before being overcome by the effects of the fire. In fire safety engineering terms, the designer must demonstrate that the ASET is greater than the RSET.

The VM defines the ASET as the time between ignition of the design fire and the time when the first tenability criterion is exceeded in a specified room in the building. These tenability criteria are identified by the VM as the following parameters being measured at a height of 2.0 m above floor level:

(a) A fractional effective dose (FED) of thermal effects greater than 0.3;

(b) Conditions where, due to smoke obscuration, visibility is less than 10 m, except in rooms of less than 100 m^2 or where the distance to an exit is 5 m or less, where visibility may fall to 5 m.

Exposure to radiation along egress routes is also briefly addressed in the VM as it is stated that occupants must not be exposed to a level of radiation that will cause pain while egressing past a window opening or a glazed panel. The criterion is that the time to onset of pain (t_p) must be longer than the exposure time (t_{exp}), however, no calculation procedures are provided in the VM, which instead refers to the "SFPE Engineering Guide – Predicting 1st and 2nd Degree Skin Burns from Thermal Radiation" for guidance.

The ASET must be calculated by modeling the design fire specified in section 2.3 in a number of locations in the building in order to find the lowest ASET for a given escape route.

2.3 Design Fires

Design fires are essential when analyzing a number of the design scenarios. The VM is concerned with three different types of design fires:

(a) Pre-flashover design fire;

(b) Post-flashover design fire;

(c) Full burnout design fire.

The individual design scenario will specify where to use which design fire, as the choice of design fire will depend on the issue being addressed in the given design scenario. For instance, if the designer wants to determine the appropriate fire resistance rating, the growth phase (pre-flash over) doesn't matter. Figure 2-2 shows an idealized design fire curve and indicates the three different stages of the design fire. The fire growth rate in the design fire is estimated as a t-squared fire growth rate, which has four categories: Ultra-fast, fast, medium and slow. The incipient phase, which is just before the growth phase, is considered too unpredictable to be included in design.

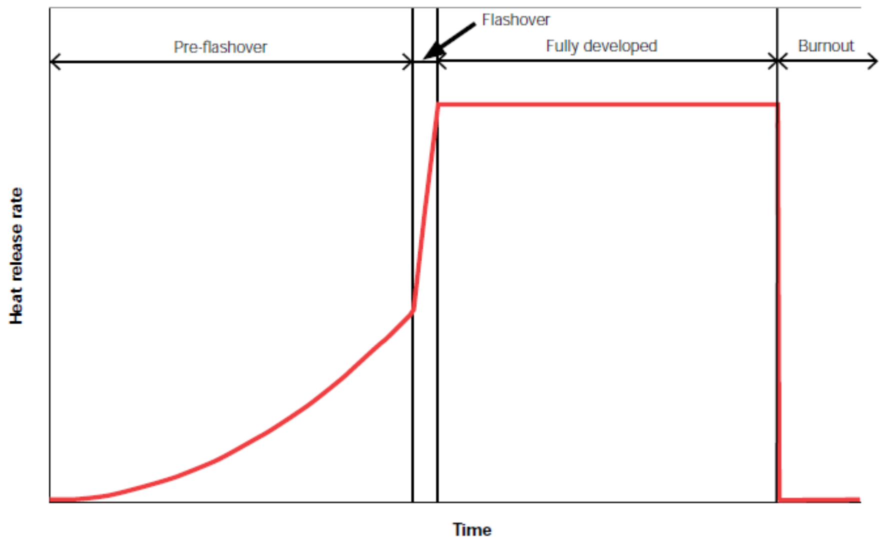


Figure 2-2: Idealized heat release rate history highlighting the four phases of conventional fire development and flashover.

The intention of the design fires is that they represent a credible worst case scenario that challenges the fire safety design of the building [16]. A design fire is defined by the following parameters:

(a) Fire growth rate;
(b) Peak HRR;
(c) Fire load energy density;
(d) Species production (water, soot);
(e) Heat flux;
(f) Time.

2.3.1 Theory behind the Idealized Design Fire Curve

The design fire curve is a description of the heat release rate of a fire as a function of time and can be divided into four phases: Ignition, growth, steady-burning and decay. No single framework for developing the entire design fire curve exists, so instead each step is typically developed separately and then brought together as a single curve [17].

The growth phase is described by a t-squared fire in the Verification Method. The t-squared fire growth can be thought of in terms of a burning object with a constant heat release rate per unit area, in which the fire is spreading in a circular pattern with a constant radial flame speed [18]. The HRR is given as the product of the mass loss rate and the heat of combustion [19], which means that the HRR in the growth phase is given as:

$$\dot{Q} = \dot{m}'' \Delta H_C v_s^2 \pi t^2 \quad (2.5)$$

Where

$\dot{Q}$	= Heat release rate
$\dot{m}''$	= Mass loss rate per unit area
ΔH_C	= Heat of combustion
v_s	= Flame speed

The HRR for a t-squared is described by:

$$\dot{Q} = \alpha t^2 \quad (2.6)$$

As a result of equations (2.5) and (2.6), it follows that:

$$\alpha = \dot{m}'' \Delta H_C v_s^2 \pi \quad (2.7)$$

Thus, the fire growth rate simplifies the description of the HRR by boiling down the mass loss rate, heat of combustion and flame speed to a single constant. Many factors influence the mass loss rate of the fuel, such as the net heat flux received at the surface and the evaporative or decomposition relationships for the fuel [18]. Also, fuel geometries that are not circular may or may not produce a t-squared fire growth.

In other words, it is an assumption that the simplification of the HRR evolution in the shape of the t-squared approximation is close enough to make reasonable fire design decisions [16].

2.3.2 Pre-flashover Design Fires

The pre-flash over fire is assumed to grow as a fast t-squared fire with the characteristics detailed in Table 2-9. Other fire growth rates and peak HRR values can be used, provided that they are technically justified and agreed upon in the design process.

The pre-flashover design fire characteristics in Table 2-9 were chosen after extensive review of literature and detailed sensitivity study applying the range of potential values to case study buildings designed according to building codes [16].

The VM offers little guidance on when to use which values in the provided ranges for the pre-flashover design fire characteristics, solely stating that the peak HRR depends on the specific fire scenario. Examples are, however, given for when to use the lower, upper or average value of the radiative fractions.

<table>
<tr><th>Building Use</th><th>Fire Growth (kW)</th><th>Species</th><th>Radiative fraction</th><th>Peak HRR</th></tr>
<tr><td>All buildings including storage with a stack height of less than 3.0 m</td><td>$0.012 - 0.047\ t^2$</td><td rowspan="4">Y_{soot}= 0.07 kg/kg
ΔH_C = 20 MJ/kg
Y_{H_2O}= 0.8 kg/kg</td><td>0.2 – 0.65</td><td>5 - 20 MW</td></tr>
<tr><td>Carparks (no stacking)</td><td>$0.012\ t^2$</td><td>0.2 – 0.65</td><td>5 - 20 MW</td></tr>
<tr><td>Storage with a stack height of between 3.0 m and 5.0 m above the floor</td><td>$0.188\ t^2$</td><td>0.2 – 0.65</td><td>Up to 50 MW</td></tr>
<tr><td>Storage with a stack height of more than 5.0 m above the floor and car parks with stacking systems</td><td>$0.00068\ t^3 H$</td><td>0.2 – 0.65</td><td>Up to 50 MW</td></tr>
</table>

Table 2-9: Pre-flashover design fire characteristics

NOTE:

t = time in seconds

H = height of storage in m

Y = yield kg/kg

ΔH_C = heat of combustion

2.3.3 Post-Flashover Design Fires

The VM deems that life safety calculations for sprinklered buildings are unlikely to be required, as the fire is expected to be controlled after activation of the fire suppression system, preventing flashover from occurring. For buildings without sprinklers, a post-flashover soot yield is set to Y_{soot} = 0.14 kg/kg_{fuel}.

2.3.4 Full Burnout Design Fires

The full burnout design fire scenario is mainly used for assessing the fire resistance of separating elements. According to the VM, design fire loads for use when modeling full burnout design fires are to be taken from the International Fire Engineering Guidelines (IFEG) 2005, section 3.4.1. The fire loads should be taken for the 80th percent fractile, which represent the current consensus values for use in Australia. The VM has listed some key values, which are shown in Table 2-10. As for the pre-flashover design fire characteristics, other design fire loads can be chosen, presuming that the fire engineer justifies it.

Occupancy	**Design fire load (MJ/m^2)**
Dwelling	870
Hospital	350
Hospital storage	3000
Hotel bedroom	400
Offices	570
Shops	900
Manufacturing	470
Manufacturing and storage not exceeding 150 kg/m^2	1800
Libraries	2250
Schools	360

Table 2-10: Design fire loads for use in modeling fires.

The VM posits three ways to model the full burnout design fire:

(a) Use a modified DtS approach with a time-equivalence formula to calculate the equivalent fire severity, specifying building elements with an FRL not less than the calculated fire severity. A minimum value of 20 minutes is required, and for sprinklered occupancies the maximum FRL is 240/240/240.

(b) Use a parametric time versus gas temperature formula or information from a relevant full scale fire test series to calculate the thermal boundary conditions for input to a structural response model or for use in a critical temperature evaluation;

(c) Use the approach specified in the SFPE Standard on Calculating Fire Exposures to Structures 2011.

The time equivalence formula suggested for method (a) is provided in the VM and is taken from Eurocode 1 Method (CEN 2002 Eurocode 1: General actions – Actions on structures exposed to fire, Brussels: European Committee to Standardisation). A sensitivity analysis is required for the percentage of windows that will break.

2.3.5 Fire Modeling Assumptions and Procedures

(a) Occupant warning systems shall be installed and assumed to be maintained and function as designed.

(b) Fire and smoke control doors with self-closers are assumed latched and closed, unless when being used by occupants. All other doors are assumed to be fully open or closed, depending on what produces the most conservative results.

(c) Smoke separations are assumed to remain in place up to the temperature at which is it exposed corresponding to the temperature at the rated time of integrity failure or until flashover occurs. If the smoke separation is not tested, it is assumed to remain in place until the average smoke temperature reaches 200°C.

(d) Windows that are not fire resisting are assumed to break at temperatures between 300°C and 500°C, or when the fire becomes limited by ventilation. A sensitivity analysis is required to evaluate the impact of partial glazing failure.

(e) The fire shall be located away from walls and corners to maximize entrainment of air into the fire plume. The base of the fire shall be located at a maximum height of 0.5 m above floor level.

(f) Fractional Effective Dose (FED) for thermal effects shall be calculated using the procedures described in ISO 13571. It shall include radiative and convective effects.

(g) For design scenario FI (section 2.4.8) only, if CFD modeling is used, the layer height shall be defined from the temperature results arranged over a number of points throughout the space.

(h) Leakage can be modeled as either a tall narrow slot from floor to ceiling or a as two vents, one at floor level and one at ceiling level, or by using a leakage algorithm. If there is a permanent opening at least five times the leakage area, the leakage may be ignored. For CFD modeling, the leakage may be increased to fit within the computation grid.

(i) Leakage through non fire-rated walls shall be modeled as follows:

    a. Smoke doors and smoke separations are assumed to have zero leakage area, except for a 10 mm gap under the doors, unless a smoke seal is specified for this gap.

b. Fire doors that are not smoke doors are assumed to have a 10 mm gap over and under the door, unless smoke seals are specified for these gaps.

c. Construction having a fire resistance rating (excluding doors) is considered to have no leakage.

d. Non fire-rated internal and external walls are assumed to have leakage areas that are proportional to the surface area of the walls. The leakage area is equal to the wall area multiplied by 0.001 m^2/m^2 for lined internal walls and external walls and 0.005 m^2/m^2 for unlined external walls.

2.4 Design Scenarios

A design scenario is defined in the VM as “the specific scenario of which the sequence of events is quantified and a fire safety engineering analysis is conducted against.” The Australian VM operates with 12 different fire scenarios, which is two scenarios more than C/VM2 in New Zealand. The scenarios are partly based on the 8 design scenarios listed in NFPA 5000 [16] [20]. The scenarios in NFPA 5000 are as follows:

- **Design fire scenario 1:** Occupancy-specific fire scenario, representing a typical fire for the given occupancy.
- **Design fire scenario 2:** Ultra-fast developing fire in the primary means of egress with interior doors open at the start of the fire.
- **Design fire scenario 3:** Fire in an unoccupied room adjacent to a high-occupancy space.
- **Design fire scenario 4:** Fire in a concealed space adjacent to a high-occupancy space.
- **Design fire scenario 5:** A slow developing fire, shielded from fire protection systems, adjacent to a high-occupancy space.

- **Design fire scenario 6:** The most severe fire resulting from the greatest possible fuel load.
- **Design fire scenario 7:** Outside exposure fire, starting at a location remote from the area/building of concern.
- **Design fire scenario 8:** Ordinary fire in a room where a passive or active fire protection system is rendered ineffective.

These scenarios have been modified and expanded so that they also cover fire spread to neighboring property, external vertical fire spread, interior surface linings and firefighting facilities. The intention of the scenarios is that they will provide a diverse range of fire events, which together will challenge the design and fire safety systems in the building. This section of the VM describes the 12 design scenarios, their required outcomes, applications, assumptions, applicable fire event and expected methods.

Design Scenario	Comments
BE – Fire blocks exit	A fire that blocks a primary means of escape.
UT - Fire in unoccupied room	A fire in a normally unoccupied room, which could potentially spread and endanger a large number of occupants in an adjacent room.
CS - Fire in concealed space	A fire that starts in a concealed space, which could potentially spread and endanger a large number of occupants in an adjacent room.
SF - Smoldering fire	A smoldering fire in vicinity to a sleeping area.
HS - Horizontal fire spread	A fire that can spread to a neighboring building due to high levels of radiation heat exposure.
VS - Vertical fire spread	A fire source exposes the external wall or openings in the building, which can lead to significant vertical fire spread

Design Scenario	Comments
IS - Rapid fire spread	A fire that can potentially ignite interior surfaces, which can lead to a rapid fire spread via the internal surface linings.
FI - Fire brigade intervention	Ensures the safe operation of firefighters in the event of a fire in the building, and to make sure that fire brigade intervention is possible.
UF - Unexpected catastrophic failure	Preventing catastrophic structural failure of any component in the building in the event of a fire.
CF - Challenging fire	The credible worst case fire scenario in a normally occupied space in the building which will challenge the design and fire safety systems of the building
RC - Robustness check	The robustness of the design is tested by assuming that a key component of the fire safety system fails.
SS - Structural stability	A building must not pose a risk to other property in the event of a fire that could potentially impact the structure of the building.

Table 2-11: All design scenarios defined by the VM.

2.4.1 BE: Fire Blocks Exit

In this scenario, a fire starts in an escape route which causes an exit to be blocked. Several analyses may have to be carried out for this scenario as the exit-blocking fire in the building can be placed at different locations that block different exits.

Required outcome: Provide a viable escape route (or multiple routes where necessary) for the building occupants.

Application: Escape routes that serve more than 50 people.

Assumptions: Active and passive fire systems in the building perform as intended by the design. The occupant tenability criteria cannot be met where fire plumes and flames block an exit.

Fire event: The fire is assumed to be located near the primary escape route or exit. The fire can be deliberately lit or accidental. Fire characteristics, such as the HRR, and analysis does not need to be considered as the fire is assumed to physically block the exit. If an RSET/ASET analysis is to be performed, the fire event will be the same fire event as described for the CF scenario, section 2.4.10.

Method: An analysis that checks whether or not a second exit is required.

Likely performance requirements: The BCA, sections CP1, CP2, CP3, CP8, DP4, DP5, DP6, DP7, EP1.4, EP2.1, EP2.2, EP4.1, EP4.2, EP4.3.

2.4.2 UT: Fire in Normally Unoccupied Room

When a fire starts in a normally unoccupied room, it can potentially migrate into an adjacent room and thereby endanger a possibly large number of occupants in that room.

Required outcome: Either demonstrate that ASET > RSET or use either separating elements or fire suppression in order to confine the fire to the room of origin.

Application: Any rooms/spaces that can hold more than 50 occupants, or rooms/spaces with less than 50 occupants but requiring extended evacuation times, if the room could be threatened by a fire occurring in another normally unoccupied space. The rooms/spaces include:

- Rooms/spaces that are physically adjacent to the unoccupied room;

- Rooms/spaces that are not fire separated from the unoccupied room;
- Rooms/spaces from which over 50 occupants or slower evacuees have to pass through a potentially threatened room/space adjacent to the unoccupied room.

Assumptions: The target space containing people is filled to capacity under normal use or otherwise contains occupants with longer evacuation times. Active and passive fire safety systems in the building perform as intended by the design.

Fire event: A design fire as described in section 2.3.2 shall be selected for the applicable occupancy.

Method: There are two expected methods for this scenario:

(a) Carry out an ASET/RSET analysis that demonstrates that the occupants within the target spaces are not exposed to untenable conditions.

(b) Include separating elements or fire suppression in order to confine the fire to the room of origin. The design criteria of the separating elements shall be based on the following:

   a. No automatic fire detection systems in building so that the separating elements shall be designed to withstand a full burnout fire.

   b. Automatic fire detection systems are installed in building so that the separating elements shall be shown to be effective for the period from ignition to the time when the occupied space (target space) is evacuated. An FRL of -60/60 is assumed to be effective for this purpose.

Likely performance requirements: The BCA, sections CP1, CP2, CP3, CP8, DP4, DP5, EP1.4, EP2.1, EP2.2, EP4.1, EP4.2, EP4.3.

2.4.3 CS: Fire in Concealed Space

This scenario deals with the same concern as the previous design scenario for a fire in a normally unoccupied room: That a fire in a concealed space can grow undetected and spread, endangering a large number of occupants in another room. It is also a concern that the ability of firefighters to assess the threat to themselves while undertaking rescue and firefighting operations might be compromised by the fire spreading in concealed spaces.

Required outcome: Demonstrate that fire spread via concealed spaces will not endanger occupants located in other rooms/spaces.

Application: Buildings with rooms/spaces holding more than 50 occupants, or rooms/spaces with less than 50 occupants but requiring extended evacuation times, that could be threatened by a fire occurring in a concealed space. The rooms/spaces include:

- Rooms/spaces that are physically adjacent to the unoccupied room;
- Rooms/spaces that are not fire separated from the unoccupied room;
- Rooms/spaces from which over 50 occupants or slower evacuees have to pass through a potentially threatened room/space adjacent to the unoccupied room.

The scenario does not apply if the concealed space has no combustibles other than timber framing and no more than two dimensions (length, width or depth) greater than 0.8 m.

Assumptions: Active and passive fire safety systems perform as intended by the design.

Fire event: None prescribed.

Method: There are three methods for this design scenario when using the VM:

(a) Use of separating elements or fire suppression in order to confine the fire to the concealed spaces.

(b) Install automatic detection systems of heat/smoke in order to provide early warning of fire within a concealed space.

(c) A combination of (1) and (2).

Likely performance requirements: The BCA, sections CP1, CP2, CP3, CP6, CP8, DP4, DP5, DP6, EP1.4, EP2.1, EP2.2, EP4.1, EP4.3.

2.4.4 SF: Smoldering Fire

A smoldering fire causes a threat to sleeping occupants.

Required outcome: Provide a safe sleeping area.

Application: Buildings where people are sleeping.

Assumptions: Active and passive fire safety systems perform as intended by the design.

Fire event: None prescribed.

Method: There are two methods for this scenario:

(a) Use of separating elements in order to confine the fire to the space of origin, assuming it is a separate space from the sleeping area. The separating elements will need to prevent all smoke ingress, which very often requires a sufficient pressure differential between the two spaces in addition to a physical barrier.

(b) Install automatic detection systems of smoke in order to provide early warning of fire within an adjoining space. If this method is chosen, then automatic smoke detection and alarm systems shall be installed throughout the sleeping and adjoining spaces.

Likely performance requirements: The BCA, sections CP2, CP3, CP8, DP4, DP5, DP6, EP1.1, EP1.2, EP1.3, EP1.4, EP2.1, EP2.2, EP4.1, EP4.2, EP4.3.

2.4.5 HS: Horizontal Fire Spread

A fully developed fire within a building can spread to a neighboring building or fire compartment due to high levels of radiation heat exposure. This can lead to ignition of the external walls of the neighboring building or other property, and therefore this scenario is created as a means to prevent horizontal fire spread to and from adjacent buildings.

Required outcome: Demonstrate that the building satisfies the heat flux requirements for spread of fire.

Application: All buildings.

Assumptions: None listed.

Fire event: The fire event will either occur in an adjacent property, or inside the building close an opening.

Method: Use the following two methods (possibly both) where appropriate.

- CV1: This method verifies compliance to avoid the spread of fire between buildings on *adjoining* allotments. The external walls of the building shall not cause a heat flux higher than those set out in column 2 in Table 2-12 at the distances set out in column 1. The external walls shall also themselves be able to withstand the heat flux limits at the same distances set out in Table 2-12.

Column 1 Location	**Column 2 Heat flux (kW/m^2)**
On boundary	80
1 m from boundary	40
3 m from boundary	20
6 m from boundary	10

Table 2-12: Horizontal fire spread - Building on adjacent allotments.

- CV2: This method verifies compliance with BCA, CP2(a)(iii) to avoid the spread of fire between buildings on the *same* allotment. The external walls of the building shall not cause a heat flux higher than those set out in column 2 in Table 2-13 at the distances set out in column 1. The external walls shall also themselves be able to withstand the heat flux limits at the same distances set out in Table 2-13.

Column 1 Distance between buildings	**Column 2 Heat flux (kW/m^2)**
0 m	80
2 m	40
6 m	20
12 m	10

Table 2-13: Horizontal fire spread - Buildings on the same allotment.

Likely performance requirements: The BCA, section CP2 (particularly CP2(a)(iii)).

2.4.6 VS: Vertical Fire Spread

A fire source exposes the external wall or the openings in the building, which can lead to significant vertical fire spread. This scenario only deals with vertical fire spread within the same building and not building-to-building fire spread as this is addressed in the previous design scenario HS.

Required outcome: Demonstrate that the building's external linings or openings do not contribute to excessive vertical fire spread.

Application: All buildings where there is a risk of vertical fire spread.

Fire event: None prescribed.

Method: Compliance to avoid the spread of fire via the external façade of a building can be verified if the façade material is:

(a) Tested in accordance with AS 5113;

(b) Exhibits behavior in AS 5113 which meets the performance requirement;

(c) Clearly labeled to display its test report classification;

(d) Installed using the same method as the test specimen;

(e) Installed only in locations described in Table 2-14 and Table 2-15.

AS5113 Class	Application	Combustible option	
		External wall fire spread requirement	Additional building requirements
A100 plus	Type A construction, greater than 100 m effective height	No combus-tible option	None
A100	Type A construction, greater than 25 m but less than or equal to 100 m effective height	EW	None
A25	Type A construction, less than or equal to effective height of 25 m	EW	None
B	Type B construction	EW	None

Table 2-14: Classification of external walls – Vertical fire spread.

Minimum Distance from boundary or adjacent build-ing	Combustible option	
	Façade fire re-quirement	Additional building requirements
On boundary or no distance between buildings	BB80	Nil
1m from boundary or 2m be-tween buildings	BB40	Nil
3m from boundary or 6m be-tween buildings	BB20	Nil
6m from boundary or 12m be-tween buildings	BB10	Nil

Table 2-15: Classification of external walls - Building to building spread.

Likely performance requirements: The BCA, sections CP2 (particularly CP2(a)(iv)), CP4, CP7, CP8, EP2.2.

2.4.7 IS: Rapid Fire Spread involving Internal Surface Linings

When interior surfaces are exposed to a growing fire, they can potentially ignite, which can lead to a rapid fire spread via the internal surface linings, potentially endangering occupants. Therefore, this design scenario is concerned with preventing the rapid fire spread involving internal surface linings.

Required outcome: Incorporation of appropriate lining materials to prevent rapid fire spread.

Application: Class 2 to 9 buildings as defined by the BCA part A3.

Fire event: None prescribed.

Method: The linings, materials and assemblies in the building must comply with the requirements listed in EN13501 or as described in Table 2-16 which is equal to table 1 in BCA specification C1.10.

Linings, material or assembly	**Requirement**
Floor linings and floor coverings	NCC Volume One Specification C1.10 Clause 3
Wall linings and ceiling linings	NCC Volume One Specification C1.10 Clause 4
Air-handling ductwork	NCC Volume One Specification C1.10 Clause 5
Lift cars	NCC Volume One Specification C1.10 Clause 6
In fire control rooms subject to BCA Specification E1.8 and fire isolated exits	NCC Volume One Specification C1.10 Clause 7
In Class 9b buildings used as a theatre, public hall or the like- (a) fixed seating in the audience area or auditorium; and (b) a proscenium curtain required by BCA Specification H1.3	
Escalators, moving walkways and non-required non-fire-isolated stairways or pedestrian ramps subject to BCA Specification D1.12.	
Sarking-type material.	
Attachments to internal floors, walls and ceilings	
Other materials including Insulation.	

Table 2-16: Internal surface lining requirements.

Likely performance requirements: The BCA, sections CP2, CP4, DP4, DP5, DP6, EP1.4, EP2.1, EP2.2, EP4.1, EP4.2.

2.4.8 FI: Fire Brigade Intervention

The purpose of this design scenario is to test the safe operation of firefighters in the event of a fire in the building and to make sure that fire brigade intervention is possible. The available firefighting facilities and the ability for the fire brigade to complete search and rescue activities must be described. The expectations of the fire event that the fire brigade will face at the estimated time of arrival must also be described.

Required outcome: Demonstrate that the fire brigade can undertake fire brigade intervention until completion of search and rescue activities.

Application: Buildings located within 50 km road travel of a fire station.

Assumptions: This scenario alone does not demonstrate that the facilities for fire brigade intervention is appropriately incorporated as it is intended to be used in conjunction with the UF scenario (section 2.4.9).

Fire event: None prescribed.

Method: The fire brigade intervention has to be facilitated to the necessary degree as shown in Table 2-17.

Facilities for Fire Brigade intervention	Building with sprinkler protection	Building without sprinkler protection
Fire Brigade External Access	Yes	Yes
Tenability to enable identification and access to seat of fire	Yes	Yes
Fire Hydrants – Internal required	Yes if > than 100 m to all points, and / or > 3 levels.	Yes if > than 70 m to all points, and / or > 3 levels.
Fire Hydrants – External required	Yes	Yes
Command and Control provisions	Yes if > 3 levels	Yes
Access to normally occupied areas for search and rescue	Yes if more than 50 persons occupy building	Yes

Table 2-17: Facilities for fire brigade intervention.

Likely performance requirements: The BCA, sections CP1, CP2, CP5, CP7, CP9, DP5, EP1.3, EP1.6, EP2.2, EP3.2.

2.4.9 UF: Unexpected Catastrophic Failure

The purpose of the UF scenario is to prevent catastrophic structural failure of any component in the building in the event of a fire. Therefore the robustness of the building is one of the main concerns of this scenario, ensuring that the building won't suddenly collapse during a fire event.

Required outcome: Demonstrate that structural failure does not occur for the extent of the fire event in order to prevent catastrophic structural failure.

Application: All buildings.

Assumptions: The scenario is to be used in conjunction with the FI (Fire Brigade Intervention) scenario in order to ensure that facilities for Fire Brigade Intervention are incorporated properly.

Fire event: None prescribed.

Method: The scenario requires an assessment of the building structure and its critical component and a systematic risk assessment of the building. In the assessment of the building structure, it must be demonstrated that it is unlikely that unexpected catastrophic failure of an isolated element due to a fire event will occur. If a building component carries a significant portion of the structure, a systematic risk assessment must be undertaken and critical high risk components must be identified and designed appropriately.

Likely performance requirements: The BCA, sections CP1, CP2, CP9.

2.4.10 CF: Challenging Fire

The fire in this scenario will represent the credible worst case fire scenario in a normally occupied space in the building, which will challenge the design and fire safety systems of the building, making this the most challenging fire of all the fire scenarios.

Required outcome: Demonstrate that ASET > RSET for design fires in different locations in the building.

Application: All buildings. The ASET does not need to be determined in enclosures of fire origin for the following fire locations:

(a) Any room with a floor area less than 2.0 m^2.

(b) Sanitary facilities adjoining the path of travel for a required exit.

(c) Any room/space of fire origin, other than sleeping areas, where care or detention is provided, and where the space has a total floor area (including mezzanine) of less than 500 m^2, more than one direction of travel or a single direction of travel that is less than 20 m and an occupant load of less than 150 people for the room or less than 100 people for any intermediate floor.

For (c) the tenability for occupants within the enclosure of origin does not have to be maintained, while it must be demonstrated that the challenging fire does not threaten the occupants in the rest of the building.

Assumptions: The overall robustness of the building is examined separately in the RC design fire scenario. There is only one fire source for each of the locations of the design fire. The active and passive fire safety systems in the building will perform as intended.

Fire event: The design fire shall be characterized with a steady state or a power law HRR, peak HRR and Fire Load Density as specified in section 2.3.2. The design fire may have to be placed in various locations, challenging the design of the buildings in any way necessary.

Method: An ASET/RSET analysis of the various design fires. The environment in the escape routes must be assessed based on the FED and visibility of the occupants. The fire calculation model can be chosen so that it is appropriate to the complexity and size of the building/space when determining the FED and the visibility.

Likely performance requirements: The BCA, sections CP1, CP2, CP3, CP8, DP4, DP5, DP6, EP1.1, EP1.2, EP1.3, EP1.4, EP2.1, EP2.2, EP4.1, EP4.2, EP4.3.

2.4.11 RC: Robustness Check

The building structure must be robust enough to prevent disproportionate spread of fire in case a key component of the fire safety system fails.

Required outcome: Demonstrate that if a single fire safety system fails, the robustness of the building will prevent disproportionate spread of fire (E.g. by showing that ASET/RSET for the remaining fire compartments is satisfied).

Application: Areas where failure of a key fire safety system could potentially expose the following groups to untenable conditions:

(a) More than 150 people;

(b) More than 50 people in a sleeping occupancy fire compartment that does not contain people that are detained or undergoing treatment or care;

(c) People that are detained or undergoing treatment or care.

Assumptions: The failure of each key fire safety system separately is assumed in this scenario.

Fire event: Identical to the fire event described for the CF scenario, section 2.4.10.

Method: Demonstrate that ASET > RSET for each of the failures of the key fire safety systems. The building must be altered until ASET>RSET for the building, apart from the room of fire origin.

Likely performance requirements: The BCA, sections CP1, CP2, CP3, CP8, DP4, DP5, DP6, DP7, EP1.1, EP1.2, EP1.3, EP1.4, EP2.1, EP2.2, EP4.1, EP4.2, EP4.3.

2.4.12 SS: Structural Stability and Other Property

A fundamental requirement of BCA 2019 is that a building must not present a risk to other property in the event of a fire. Therefore this scenario has been designed so that it can be demonstrated that a building will not pose a risk to other property in the event of a fire that could potentially impact the structure of the building.

Required outcome: Demonstrate that the building does not present a risk to other property in a full burnout scenario.

Application: All buildings.

Assumptions: There is only one fire source for each of the locations of the design fire. As occupant egress has already been assessed in the CF scenario, it is not a concern in this scenario.

Fire event: The full burnout design fire described in section 2.3.4. The worst credible fire case shall be located within any space of the building and not just within an occupied space. Several different fire design locations may be required to be tested in order to find the worst credible fire.

Method: Undertaking an analysis of the building structure that demonstrates that appropriate features have been incorporated into the building which either prevents the building structure from collapsing within the burnout scenario, or ensures that, if failure does occur within the burnout scenario, the building will collapse inwards. The burnout design fire must take place in the credible worst case location for the structural stability of the building.

Likely performance requirements: The BCA, sections CP1, CP5.

Chapter 3 Execution of Performance-Based Design

In this chapter, a performance-based design (PBD) of the building will be completed. The PBD is considered to represent the ideal design of the building, as it allows for optimization without over- or under-design of the building. Nonetheless, it must be emphasized that the final result of the PBD application is not exhaustive and merely serves as an example of an ideal design. In other words, additional ideal designs are possible as not all conceivable outcomes for the building have been examined in this project. E.g. an alteration of the performance criteria could easily result in alternate building designs. Generally, there is no universal benchmark for an ideal fire safety design of a building.

The process of the PBD is partly general for the entire building, but was mainly applied to the three different occupancy categories separately. These three categories are:

- The car park basement;
- The retail ground floor;
- The upper office/library floors.

3.1 Building Characteristics

The building is a new high-rise building of eight stories above ground and two basement levels. The base of the building is 788 m^2 and the height from the ground to the roof is 31.4 m, while the height to the highest floor is 24.9 m. The purpose of the building is mixed use, so that the basement levels are car parking areas, the ground floor is used for retail and the seven upper floors will be used for office space with a library on half of the first floor. The building is located 3 km away from the nearest fire brigade.

The loadbearing structure, the floors and the roof are made of concrete, while the external walls are double-glazed curtain walls, and the internal walls are timber studs at 600 mm centers lined with 10 mm standard plasterboard on each side. The ceiling is standard 10 mm plasterboard, and the internal wall lining to common areas (corridors, stairways, lift lobby) is made of pine.

3.1.1 Basement Levels – Car Park

Figure 3-1: Floor plan of car park basement levels, B1 & B2.

The two basement levels, B1 and B2, consist of 750 m^2 car parking area each with 14 parking spaces on each level. The height from the floor to the ceiling is 2.75 m, while it is 3.25 m from floor to floor. Vehicles have access through a ramp that leads from the floors to terrain level. The end of the ramp is open to the outside. There are two exits meant for occupants, the elevator and the central staircase in the building. The staircase and the elevator also connect to the upper floors.

The two basement stories make up one compartment together, as these cannot be fully separated due to the vehicle ramp cutting through the ceiling/floor. The parking area and the staircase are separated by a small compartment which will be referred to as a safety compartment.

3.1.2 Ground Floor – Retail Story

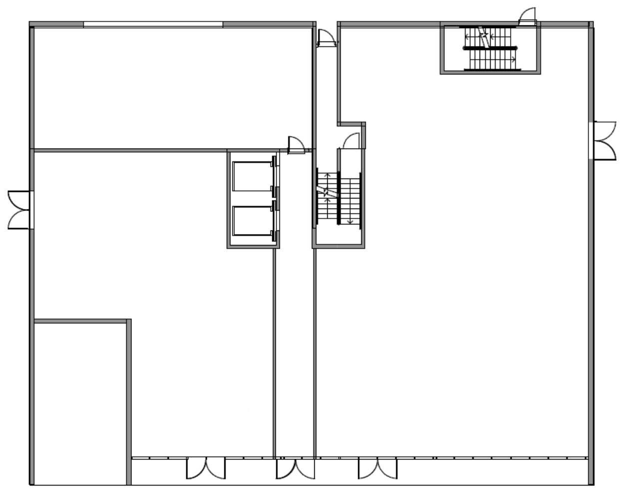


Figure 3-2: Floor plan of the ground floor

The ground floor of the building is intended for retail space, which consists of two stores and a storage area in the back of the building. The smaller of the two stores is 170 m2, the larger one is 320 m^2 and the storage area in the back is 108 m^2. The height from floor-to-floor is 3.9 m, while the height from floor-to-ceiling is 3.0 m. Other than the two stores and the storage area, there is a corridor, an elevator shaft and two staircases on the ground floor.

The stores are not connected to the rest of the building, nor each other, while exits from these areas lead directly to the outside terrain. The storage area is connected to the outside by a long corridor that runs in the middle of the building. This corridor is also connected to the elevator shaft. The two staircases are not connected to any spaces on the ground floor either.

All of these separated areas are divided by compartment walls in order to keep fire and smoke from moving between the areas. Therefore the following areas are enclosed by compartment walls:

- Each of the two stores;
- The storage area in the back;
- The corridor;
- The elevator shaft;
- Each of the two staircases.

The only compartments that are connected on this floor are the storage area and the corridor, and the corridor and the elevator shaft.

3.1.3 Upper Floors – Office & Library

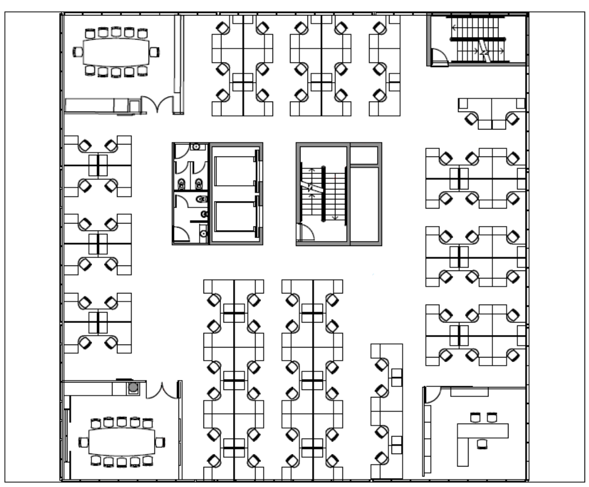


Figure 3-3: Floor plan of office floors, L1-L2. Half of the first floor consists of library, while the 6th and 7th floor are connected by an open internal staircase in the lower left corner.

The upper floors all consist of 620 m^2 office space on each floor, except for the first floor, where half of the area is a library. The office space mainly contains desks, chairs, office furniture, meeting rooms and two restrooms. The floors are all connected to the ground level through two staircases which act as the main exits. The central staircase goes all the way to the basement floors, while the staircase in the upper right corner stops at terrain level.

Each of the stories makes up their own compartment, separated by compartment floors, except for the two top floors. As the two top floors are linked by an open stairway in the lower left corner, these will act as one compartment together. Other than entire stories, the only compartments on the upper floors are the two staircases and the elevator compartment.

3.2 Occupant Characteristics

The occupant density has been determined as the heaviest occupant load between the standards from USA, UK and Australia. This lead to the following occupant loads:

- Basement levels: 28 occupants/floor (UK Standard)
- Ground floor:
    - Retail area: 2.0 m^2/person (UK Standard)
    - Storage area: 27.9 m^2/person (USA Standard)
- Upper floors:
    - Office area: 6 m^2/person (UK Standard)
    - Library: 7 m^2/person (UK Standard)

The average speed of the occupants is set to 1.17 m/s with a standard deviation of 0.22 m/s [24]. The occupants are also assumed to be aware and wake while they are in any part of the building. The occupants in the retail area and in the car park are assumed to be unfamiliar with the building, except for the staff who will be trained in appropriate actions during an emergency. The occupants in the remaining parts of the building are assumed to be familiar with the space.

3.3 Fire Strategy

The typical components of the fire safety strategy of a high rise building are the evacuation strategy, containing the fire, containing the smoke, preventing the building from collapsing and firefighting access [25].

This building is divided into three different hazards: The two basement floors; the retail ground floor and; the seven upper office floors. These three hazards will have different levels of redundancy.

The evacuation process in a high rise building relies on the stairways as the occupants cannot be rescued from the outside. There will be two protected stairways in the building as one stairway is added as a redundancy in order to provide the occupants with an alternative escape route on each upper story in case one of the stairways will be compromised. The elevators will not be used for evacuation. The stairways are protected by compartment walls in order to keep the fire and the smoke out and also by pressurization in order to keep the smoke out, making the overall system more robust. The stairway doors will be fire resistant self-closing doors to help keep the fire and smoke out of the stairways.

The building will be divided into fire compartments in order to contain the fire and the smoke, so that occupants on all floors will not be required to evacuate simultaneously. All floors (except the floor between the two basement floors) will be compartment floors in order to prevent vertical fire spread between stories. This means that each story is its own compartment from the ground floor and up, while the two basement floors constitute one compartment together. Only the occupants on the fire floor, the floor below and the floor right above the fire floor will be evacuated initially. However, if the fire is detected on the ground floor, both basement floors will evacuate. The occupants on the three stated floors will be notified of the fire by an alarm system, which will be activated by an automatic detection system. The alarm system can also be activated by a manual detection system, if the fire is observed by an occupant before being detected by the automatic detection system. The alarm system is not dependent on further verification other than the automatic detection system itself in order to start notifying the occupants on the three evacuating floors.

Upon arrival, the firefighters will have control of the building, its fire safety systems and its occupants. The occupants from the three (or four) evacuating floors will already have left the building, when the firefighters arrive, so that cross flow in the stairways will not be an issue. The time expectations of how long it will take the evacuees to leave the building and how long it will take the firefighters to arrive are consistent with the fire strategy of the building. The firefighters will attend to the fire event and will be responsible of notifying the remaining occupants in the building if it is deemed necessary to evacuate the remaining parts of the building. The remaining occupants will upon notification from the firefighters begin evacuating simultaneously.

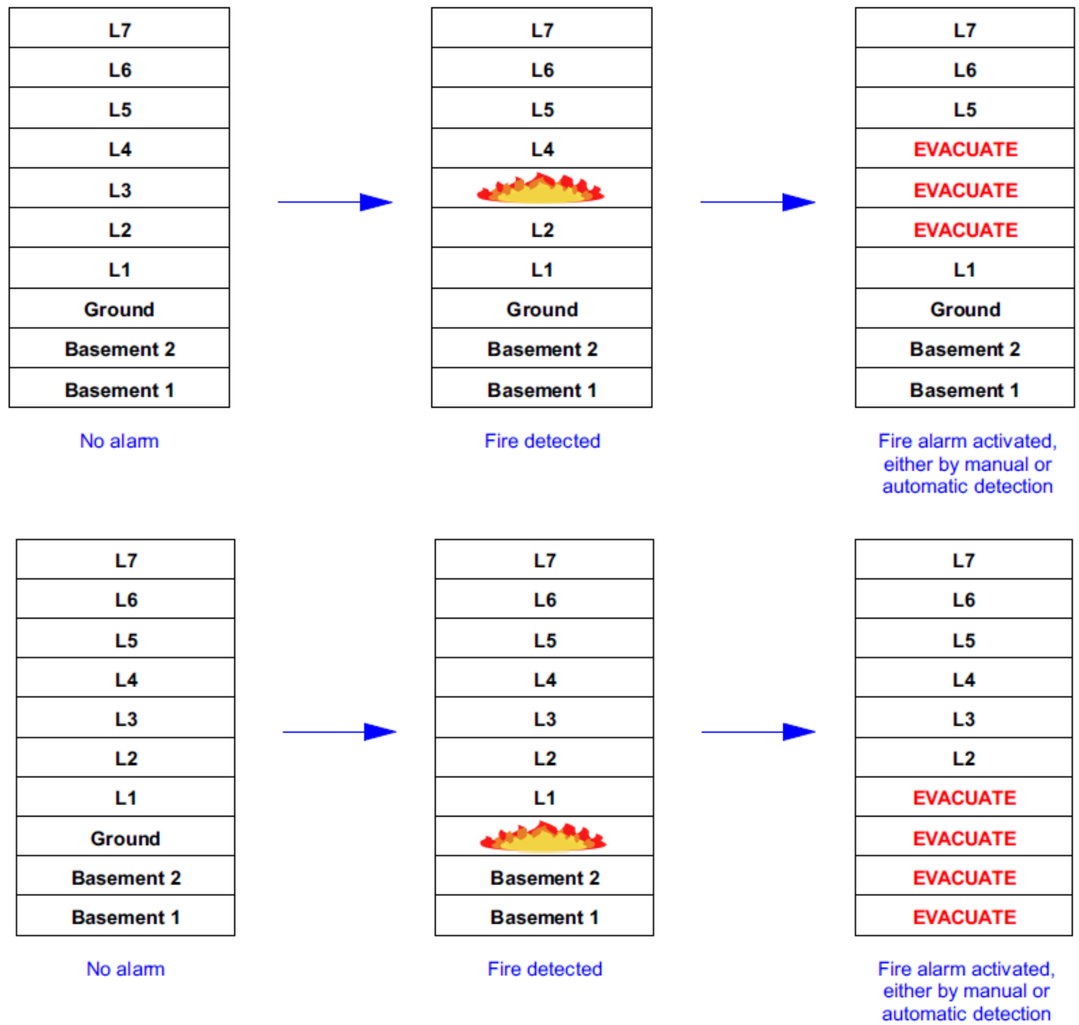


Figure 3-4: Examples of evacuating floors according to the fire strategy, when a fire is detected in the building.

Each of the shops on the ground floor will have access to two exits as one of the exits are added as a redundancy in order to provide the occupants with an alternative escape route in case one of the exits will be compromised. The back of the house has access to a corridor, which will be protected as a fire compartment as it acts as the only exit. The entire floor will be notified and evacuate if a fire is detected anywhere on the ground floor or in the basement. The occupants in the basement will have access to two exits, one of the stairways and the ramp. In this case, the ramp will act as the redundant exit.

The loadbearing structures and compartment assemblies in the building will be designed so that they do not affect or endanger any building occupants for as long as it will take the fuel load in the building to burn out.

The elevator will be used as a firefighting shaft and will therefore be protected by compartment walls and pressurization. It will provide access for the firefighters to the stories in the building. On the basement floors, the safety compartment that leads from the parking area to the elevator and the stairway will be protected by compartment walls as a redundancy.

3.4 Design Goals, Objectives and Performance Criteria

3.4.1 Objectives

The objectives have been developed based upon the fire strategy and the overall main protection goal that is the life safety of the occupants. The objectives are:

1. Allow enough evacuation time for the people on the fire floor, the floor below and the floor above to evacuate the building;
2. Maintain safe and tenable egress conditions for the evacuating occupants without exposure to smoke or heat;
3. Ensure that occupants are able to find exits until they have evacuated the space;

4. Preserve the structural integrity of the building by preserving the loadbearing capacity of the concrete for long enough for burnout to be reached.

3.4.2 Performance Criteria

As the defined objectives are not detailed enough for evaluation of trial designs, the objectives will have to be quantified into performance criteria. Performance criteria are numerical values that can be predicted with engineering tools such as models, and establishing them is considered one of the most challenging aspects of conducting a performance-based design of a building [26].

Design Goal	Design Objectives	Performance Criteria
Life safety of occupants	1. Allow enough evacuation time for the people on the fire floor, the floor below and the floor above to evacuate the building.	RSET < ASET as a function of the risk being analyzed.
	2. Maintain safe and tenable egress conditions for the evacuating occupants without exposure to smoke or heat.	Limit average height of smoke layer above floor to 2.1 m
		Maintain an average ambient temperature below 45^{o}C.
		Maintain a smoke layer temperature below 200^{o}C.
	3. Ensure that occupants are able to find exits until they have evacuated the space.	Limit average height of smoke layer above floor to 2.2 m
	4. Preserve the structural integrity of the building by preserving the loadbearing capacity of the concrete for long enough for burnout to be reached.	Preserve structural integrity of the basement, ground floor and 1st floor for at least 380 minutes and 170 minutes for the remaining upper floors.

Table 3-1: Goals, objectives and performance criteria.

For the first objective, the performance requirement is that the Required Safe Egress Time (RSET) has to be shorter than the Available Safe Egress Time (ASET). Therefore, an ASET vs. RSET analysis must be performed.

The performance criteria for the second objective are based on threshold values defined in the *Fire Engineering Design Guide* [27] and the *SFPE Handbook of Fire Protection Engineering* [28]. High levels of convective heat can lead to skin pain or burns, while inhaling the hot gases can lead to strokes. Humans can withstand being exposed to convective heat of 60^0C for 30 minutes before it leads to incapacitation. However, threshold pain is already felt by humans when the average temperature of the pain receptors located at an approximate skin depth of 0.1 mm is increased to ca. 45^0C, leading to the performance criterion of an ambient temperature of maximum 45^0C. The radiant heat from the smoke layer above the occupants can cause erythema and skin burns. The radiant heat flux from the upper layer should therefore not exceed 2.5 kW/m^2 at head height, which corresponds to an upper layer temperature of approximately 200^0C.

The 2.1 m is chosen to ensure that the smoke layer is above head height for all occupants. This criterion is, however, overridden by the other smoke layer height criterion: That the smoke layer interface height must be at least above 2.2 m. The latter of these two criteria is based on the expected height of the exit signs in the space.

The performance criterion for objective 4 has been developed based on a time equivalence calculation for the fire severity in the building (see Appendix A).

3.5 Design Fire Scenarios

Fire scenarios consist of three elements [6]:

- Fire characteristics:
    - First item ignited
    - Fire growth
    - Flashover
    - Full development
    - Decay
    - Extinction
- Building characteristics:
    - Physical features
    - Contents of room/building
    - Ambient environment within the building
- Occupant characteristics:
    - Ability of occupants to respond and evacuate during a fire emergency.

Her Majesty's Government's *Fire safety Risk Assessment Guide for Offices and Shops* [29] lists potential sources of fuel that are common in office buildings and shops. For the building in question, the relevant potential sources of fuel in the building listed in the guide are:

- Flammable-liquid-based products (paints, varnishes, thinners and adhesives);
- Flammable liquids and solvents (white spirit, methylated spirit, cooking oils and disposable cigarette lighters);
- Flammable chemicals (certain cleaning products, photocopier chemicals and dry cleaning that uses hydrocarbon solvents);
- Packaging materials, stationery, advertising material and decorations;
- Plastics and rubber (video tapes, polyurethane foam-filled furniture and polystyrene-based display materials);
- Textiles and soft furnishings (hanging curtains and clothing displays);

- Waste products, particularly finely divided items such as shredded paper and wood shavings, off cuts, and dust; and
- Flammable gases (liquefied petroleum gas (LPG)).

There are other potential sources of fuel than those listed above. Office furniture and equipment such as desks and computers may also pose as potential fuel sources. Also, in the car parking areas in the basement, the vehicles and the gasoline within them also pose as a potential source of fuel.

While it is important to be aware of the potential ignition sources in the space of the building, it is not necessary to describe the specific source of ignition for a design fire scenario when designing for fire safety. When designing a building for fire safety, it shall always be assumed that ignition will happen without regards to the number of potential ignition sources in the space. It is therefore more essential to identify the fuel loads in the building, and based on them determine a severe fire scenario which will challenge the design of the building.

Statistics

The NFPA creates its own reports and statistics on fire incidents which can be used to identify the fire scenarios that are most likely to occur in a certain type of building. The fire incident data is sorted by property types, such as business, mercantile and high-rise buildings [30][31][32].

According to the data, the leading causes for fires in both office spaces and stores are cooking equipment, electrical distribution and lightning equipment and heating equipment. The first item ignited is typically cooking materials, electrical wire or cable insulation or rubbish/trash/waste, again for both offices spaces and shops. However, the leading areas of origin differ from one another, as a fire in an office building is most likely to originate in a cooking area or in the office space, while the most common areas for mercantile spaces are kitchens, laundry rooms, unclassified out-sides areas and sales/showrooms.

3.5.1 Car Park

The main fuel loads in the car park basement consist of vehicles. As the floor plan of the basement shows, one level of the car park basement can contain 14 cars, and up to 10 cars are placed right next to each other.

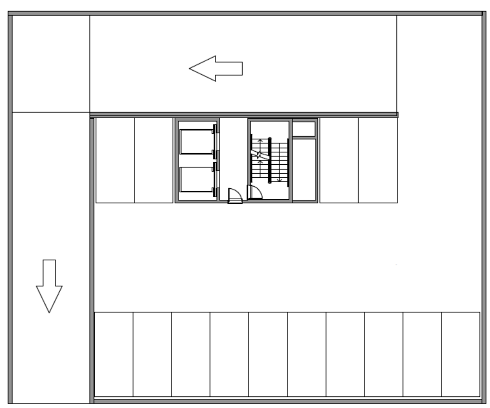


Figure 3-5: The floor plan shows 14 car park spaces. Up to 10 of these car parking spaces are located side by side.

The fire characteristics of the vehicles depend on the type and size of the different cars. The research paper *Multiple Vehicle Design Fire Scenarios in Car Parking Buildings* [33] arranges some of the different vehicle types into eight different groups: Passenger cars, which are subdivided into mini, light, compact, medium and heavy, sport-utility vehicles, multi-purpose vehicles and unclassified vehicles. The medium passenger car possesses the most severe fire characteristics measured, which are shown in table Table 3-2. These fire characteristics will represent the characteristics of any car in the car park basement. The characteristics are based on the HRRs shown in Figure 3-6.

Peak HRR [kW]				Time to peak [min]				Total energy released [MJ]			
Mean	Standard deviation	Max. value	Min. value	Mean	Standard deviation	Max. value	Min. value	Mean	Standard deviation	Max. value	Min. value
6843	2797	9854	3650	37.2	7.4	46.9	26.0	6386	695	7000	5960

Table 3-2: Statistical data for the peak HRR, the time to peak and the total energy released for a medium sized car according to M. Z. M. Tohir's research [33].

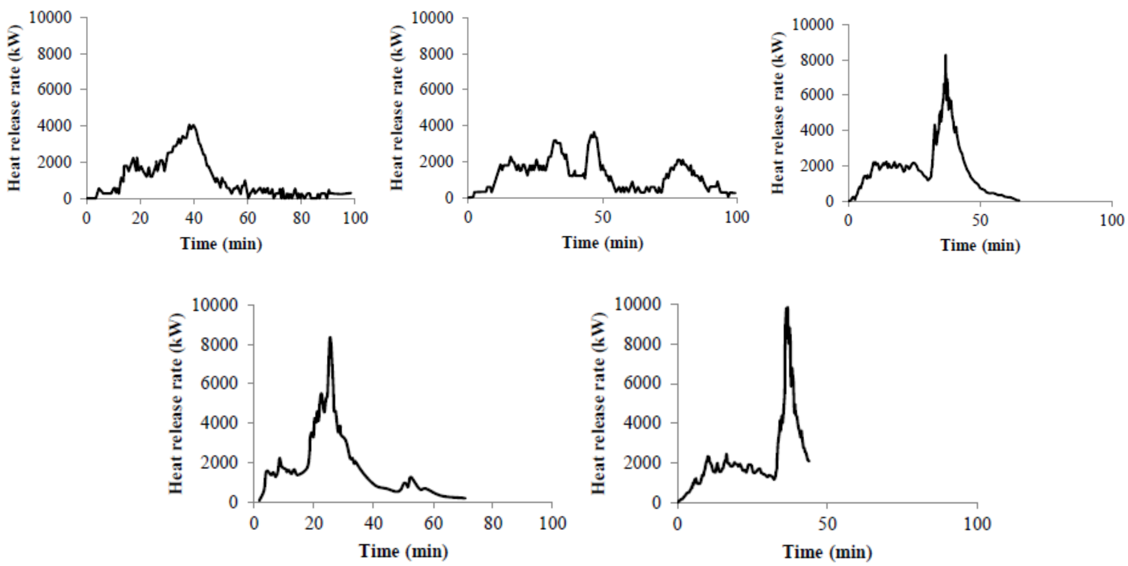


Figure 3-6: Measured HRRs for five different burning medium sized cars (Reproduced from M. Z. M. Tohir's research [33]).

Other than these fire characteristics, the HRR evolutions for the medium passenger cars shows that it takes between 65 and 100 minutes before the vehicle fire is extinguished. The paper also states that after one vehicle was ignited, it took 20 minutes before the vehicle next to it ignited as well. A third vehicle was placed next to the two other vehicles, however with one space in between (see Figure 3-7), and this vehicle was ignited after 22-25 minutes after the ignition of the first car.

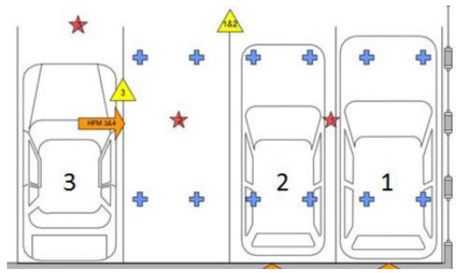


Figure 3-7: Placement of cars in experiment for fire spread between vehicles (Reproduced from M. Z. M. Tohir's research [33]).

Based on this information, a medium sized passenger car would in average have a peak release HRR of 6843 kW and a total energy release of 6386 MJ. Therefore all 14 vehicles on one level in the basement would release 95,802 MJ of energy together. This is in agreement with a suggested design fire load energy density of 260 MJ/m^2 [34] where the area value assumed is 25 m^2/parking space, resulting in a total energy release of 91,000 MJ.

A vehicle burns slowly, as it can take up to 100 minutes before the fire is extinguished, however, it can spread to several cars simultaneously after 20-25 minutes after ignition. This means that, in theory, flashover could happen within 25 minutes on a basement level. The maximum peak fire growth measured out of the five fire tests of medium cars was measured to 0.00358 kW/s^2 (slow fire).

In another case study, an actual fire in a car park in Rotterdam was investigated [35]. The incident involved seven cars where six of them ignited. Two scenarios were modeled, and scenario 1 showed the highest peak HRR. The individual HRRs for each of the cars shown in Figure 3-6 match the HRR per car used in the Rotterdam study fairly, as it is set to ca. 8300 kW as seen in Figure 3-8. Figure 3-9 shows the total HRR from the Rotterdam car park, and the sudden rise in HRR indicates that flashover happens 25 minutes after initial ignition, which is in good agreement with the research paper.

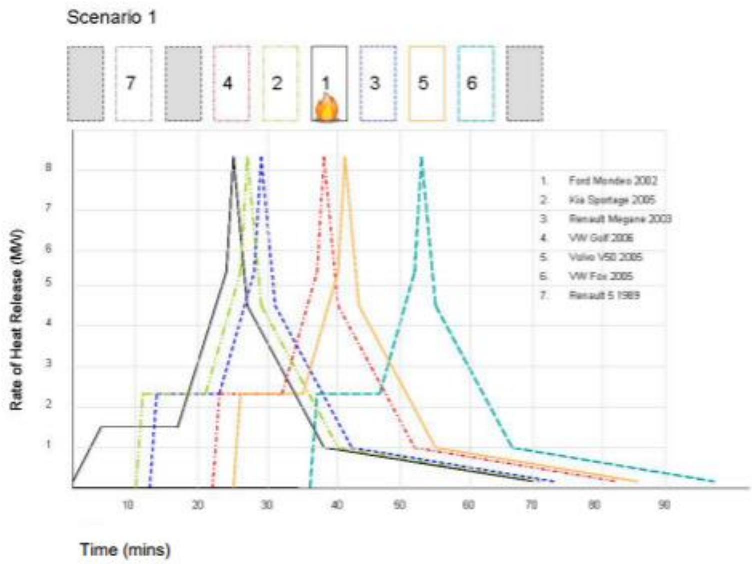


Figure 3-8: Theoretical HRRs from Rotterdam Car Park investigation (Reproduced from Efectis Nederlands-report [35]).

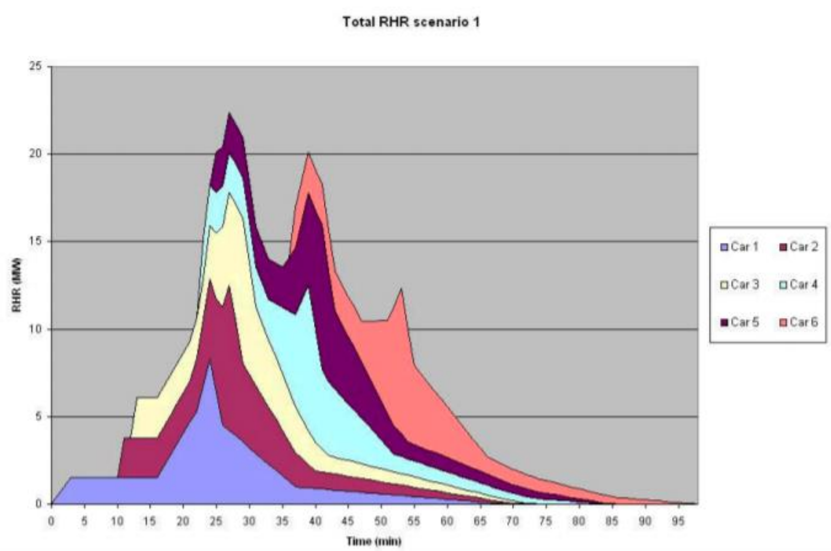


Figure 3-9: Theoretical total HRRs from Rotterdam Car Park investigation (Reproduced from Efectis Nederlands-report [35]).

3.5.2 Office spaces

The office levels (L1-L7) typically contain office furniture such as workstations, filing cabinets, telephones, chairs, computers, office paper, waste baskets etc. Several surveys have been conducted with the intention of defining design fuel loads for common occupancy classifications such as office spaces. For this building, the fuel load data in Table 3-3 from IFEG 2005 will be used as reference [36].

International Fire Engineering Guidelines (IFEG 2005) Fuel Load Table			
Mean	**95% Fractile**		
[MJ/m^2]	**[MJ/m^2]**	**[kg/m^2]**	**[lb/ft^2]**
420	760	42	9

Table 3-3: Design fuel loads for offices areas from IFEG 2005.

It is noted that the mean values should not be used for design fires as at least half of the buildings is expected to exceed the mean value. Therefore the maximum, or in this case the 95% fractile, should be used for design purposes.

HHR characteristics will be taken for a clerical workstation (including small filing cabinets, telephones, chairs, computers, and a modest amount of office paper) with four desk units without partition panels. The peak HRR is 3035 kW, which it takes 508 s to reach [37]. The HRR evolution is shown as the “test 1” line in Figure 3-10 below. A waste basket next to the work station showed a peak HRR of 50-60 kW.

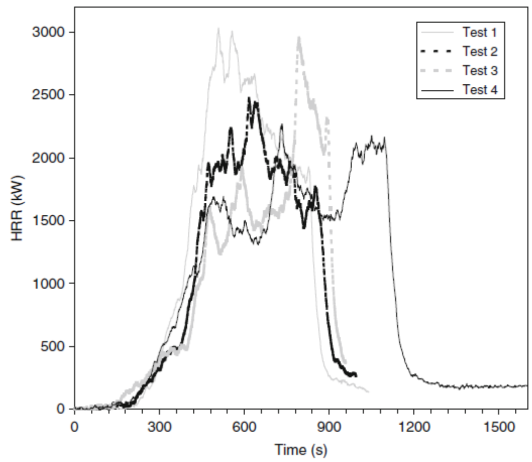


Figure 3-10: HRR evolution for a clerical workstation. Test 1 proposes the most severe HRR (Reproduced from SFPE Handbook [37]).

In a free-burn experiment which was conducted for four desk units (with and without partitions) that were all situated as depicted on Figure 3-11, the fire spread between the four desk was determined. It was measured that it took ca. 7 minutes to spread to a desk unit that was placed right next to the burning desk unit, while it took ca. 14 minutes to spread to the desk unit placed diagonally opposite the first burning unit [38]. Presumably, the spread to the remaining desk units in the office space will become faster as the ambient temperature in the compartment will keep rising after ignition. The compartment that the experiment took place in is also significantly smaller than the open space that constitutes an actual office level in the building. Therefore, the fire spread is assumed to be more severe in the experiment than in the actual building, which is why the experimental data is conservative when used to model the building.

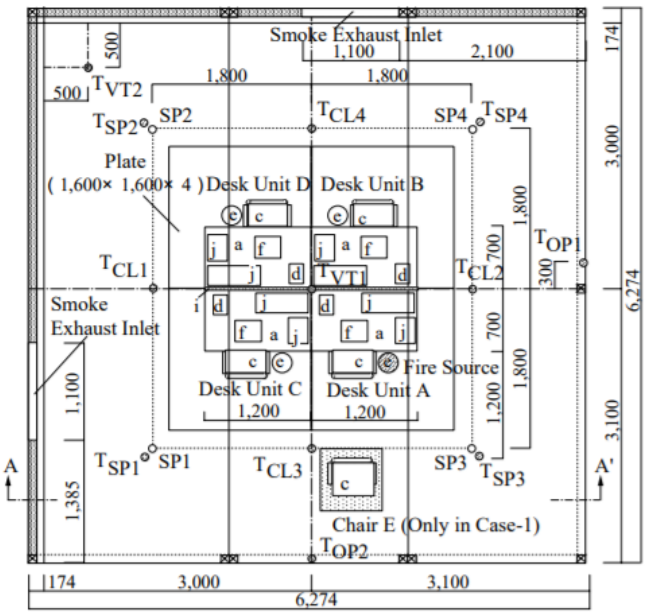


Figure 3-11: Placement of workstations during free burn experiment (Reproduced from S. Kakegawa's research [38]).

Data from fire investigations from London Fire Brigade's real fire library has been used to analyze fire sizes and fire growth rates for different occupancies [39]. 25 fires in office buildings have been analyzed, and the fire growth rate was found to be log-normal distributed with a 95% fractile of $\alpha_{95} = 0.016 \ \frac{kW}{s^2}$ (medium fire).

There is no guarantee that the office space in the building will always contain the same type of furniture as the current floor plan displays. Thus, it might be worth considering additional potential fuel sources. It is not uncommon to see e.g. a sofa in an office, which, as Figure 3-12 shows, has a peak HRR of ca. 3000 kW that is reached after 200 s. The sofa has a fire growth rate of $\alpha = 0.1055 \ \frac{kW}{s^2}$ (fast fire). The sofa fire therefore spreads faster, possibly reducing the time to flashover significantly.

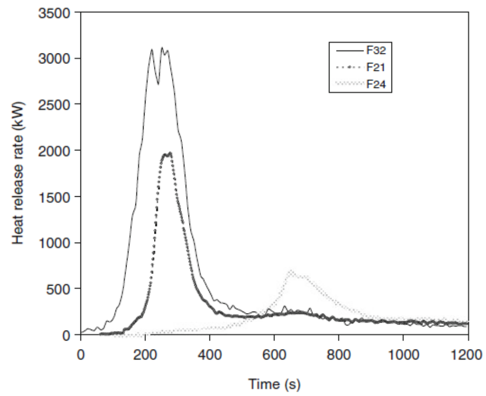


Figure 3-12: HHR for a burning 2-persons sofa (Test F32) (Reproduced from SFPE Handbook [37]).

3.5.3 Retail Space on Ground Floor

The ground floor of the building consists of retail space, containing two shops and a storage room in the back of the building. There is given no information as to what types of shops the ground story is meant to host and what types of combustibles they will contain. The severity of a potential fire on the ground floor is highly dependent on the content of the shops, which can store anything from textiles and books to flammable liquids. However, it is considered sufficient for the scope of this project to consider the space as standard mercantile space. The fuel load data for a standard shop is shown in Table 3-4 [36].

International Fire Engineering Guidelines (IFEG 2005) Fuel Load Table			
Mean	**95% Fractile**		
[MJ/m^2]	**[MJ/m^2]**	**[kg/m^2]**	**[lb/ft^2]**
600	1300	72	16

Table 3-4: Design fuel loads for retails areas from IFEG 2005.

Data from fire investigations from London Fire Brigade's real fire library has been used to analyze fire sizes and fire growth rates for different occupancies [39]. 94 fires in retail buildings have been analyzed, and the fire growth rate was found to be log-normal distributed with a 95% fractile of $\alpha_{95} = 0.101\ \frac{kW}{s^2}$ (fast fire).

The peak HRR will be the maximum peak heat release measured in different tests that were conducted in connection with a survey of 168 different types of stores. The measured HRRs and the different kinds of shops that were tested are shown in Figure 3-13. Out of all these tests, the highest HRR was measured to 2700 kW (Fast food outlet), which will therefore act as the peak HRR for the standard mercantile space.

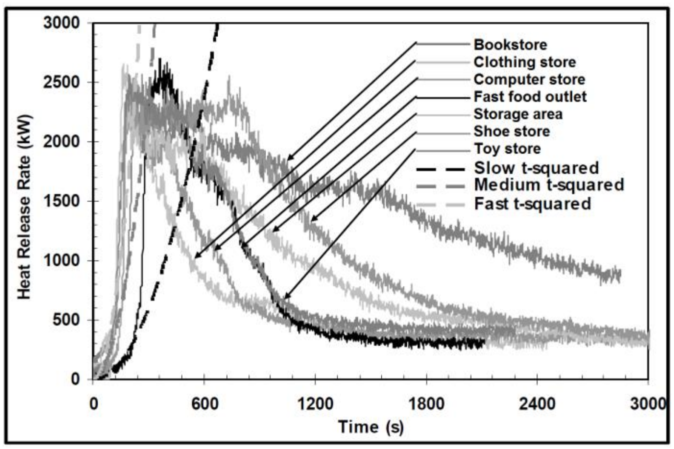


Figure 3-13: HRRs for different types of stores (Reproduced from G. Hadjisophocleous' research [40]).

3.5.4 Library

On the second floor, half of the area (310 m^2) is categorized as a library, which has different fire characteristics from the rest of the office space. The fuel load characteristics for libraries are shown in Table 3-5 [36]. The fuel load for the library area is higher than that of one story of office space.

International Fire Engineering Guidelines (IFEG 2005) Fuel Load Table			
Mean	**95% Fractile**		
[MJ/m^2]	**[MJ/m^2]**	**[kg/m^2]**	**[lb/ft^2]**
1500	2750	153	34

Table 3-5: Design fuel loads for libraries from IFEG 2005.

A study involving two free-burn experiments of open shelves has been conducted [41]. The shelving units used in the experiments were 1.8 m tall by 0.91 m wide by 0.46 m deep with a weight of 9.98 kg, and a total of four of these units were used in each test. The units were placed in two parallel sets of back to back units with an aisle in between. The units were loaded with paper products (120 kg per unit), making the units able to represent the library units of the building.

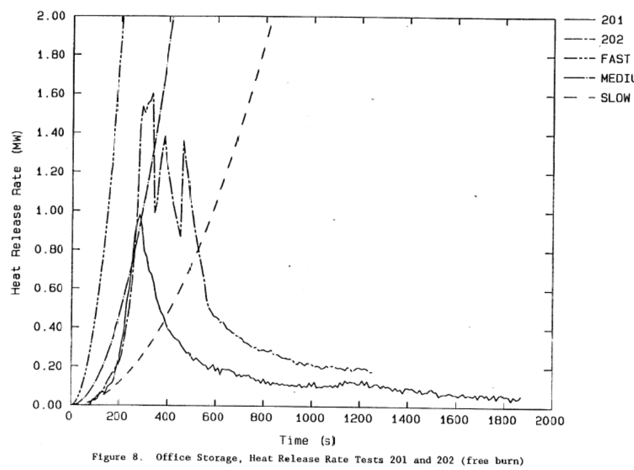


Figure 3-14: HRRs for free burning of open shelves (Reproduced from W. D. Walton's research [41]).

For the two experiments (201 and 202 on Figure 3-14), the initial growth rate α tended to follow the rate of a medium squared fire ($\alpha = 0.012\ \frac{kW}{s^2}$), while after 200 sec it tended to follow the slope of a fast squared fire ($\alpha = 0.047 \frac{kW}{s^2}$). While the fast fire growth rate curve can be used for modeling the fire in the library, the peak HRR measured in the experiments while most likely differ from the peak HRR in a potential fire in the actual library. The maximum total heat released from the two experiments was only 560 MJ, while the design fire load used in library will be 2750 MJ/m^2. It is therefore estimated that the peak HRR will have to be higher than 1.60 MW. As an approximation, the peak HRR for the bookstore shown in Figure 3-13 will be used, which is 2375 kW [40]. This HRR value is considered a conservative assumption as the fire load for the given bookstore is higher (5305 MJ/m^2) than the fuel load chosen for the library. Also, for this peak HRR value for a bookstore, the initial growth rate is expected to be small/medium instead of medium/fast, however, a medium/fast growth rate will still be used for modeling as it is a conservative assumption.

3.6 Trial Designs

3.6.1 Retail Space

For the ground floor, several trial designs will be evaluated. These trial designs will include:

- Manual detection systems;
- Automatic detection systems;
- Fire suppression systems;
- Egress provisions.

Smoke control by the use of mechanical ventilation systems was also looked into when examining trial designs for the building. However, when exhausting air out of a room by the use of mechanical ventilation, a minimum smoke layer depth is required in order to avoid plugholing. Plugholing is when air from below the smoke layer is pulled through the smoke layer and into the exhaust. This phenomenon can cause system failure as the exhaust from the smoke layer is reduced, possibly resulting in a lower smoke layer than intended, leading to the occupants becoming exposed to the smoke.

Plugholing can occur if the smoke layer is too shallow. Therefore the minimum design smoke layer depth as a rule needs to be 20 percent of the floor-to-ceiling height. The 20 percent is determined by both the depth required to prevent plugholing and the thickness of the ceiling jet that will be formed after a smoke plume reaches the ceiling. When the ceiling jet meets a wall, the smoke flow will turn down and travels back underneath the ceiling jet as shown on Figure 3-15. The estimated thickness of this ceiling jet is 10 percent of the floor-to-ceiling height, and the smoke flow underneath the ceiling jet is also 10 percent of the floor-to-ceiling height. Combined, the ceiling jet and flow underneath it lead to a required 20 percent of the floor-to-ceiling height thick smoke layer [42][43].

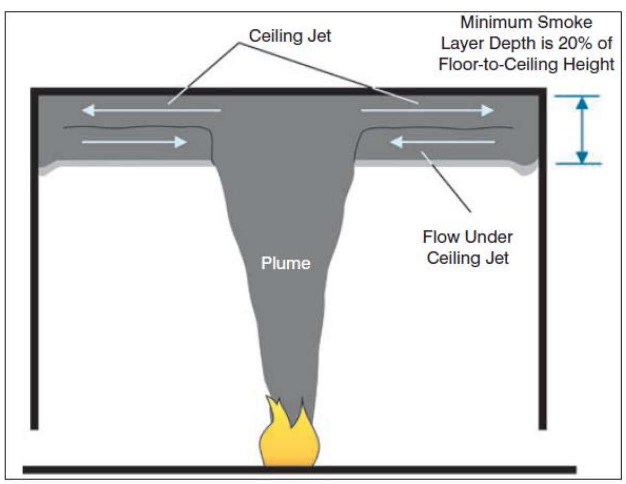


Figure 3-15: Illustration of design smoke layer depth (Reproduced from J. H. Klote's research [43]).

The highest floor-to-ceiling height in the building is on the ground floor, where it is 3.0 m, resulting in a minimum design smoke layer depth of 0.6 m. As the performance criterion for the smoke layer interface height is 2.2 m, this requirement of a design smoke layer depth doesn't allow much additional space before the performance criterion is exceeded. Relying on a smoke control system to achieve a satisfactory level of safety would therefore create a risk that occupants could be exposed to smoke.

3.6.1.1 Manual detection

When it comes to determining the manual detection time, there are no explicit guidelines. The manual detection time is based solely on judgment from the designer, who will have to perform a qualitative evaluation of several factors such as room occupancy, frequency of routine entry into a room, general room accessibility and fire severity [44].

In the design scenarios, the building is fully occupied by people that are awake and aware of their surroundings, and the fire will be very severe. Therefore the manual detection time (including notification time) will be estimated as the time that it takes the smoke layer depth to reach 5 % of the ceiling height.

3.6.1.2 Automatic detection

Providing the space with an automatic detection system will reduce the RSET as the detection time will be lowered. The automatic detection time will be determined by CFAST simulations, where smoke detectors will be implemented in the model. The smoke detectors will activate when an obscuration level of 14%/m is reached. This value poses as a reasonable estimate of when a majority of smoke detectors will alarm according to research conducted by Geiman and Gottuk [45]. The smoke alarms will not have a delay between detection the fire and notifying occupants, thus making the notification time equal to 0 s.

3.6.1.3 Fire Suppression System

One of the trial designs will include a fire suppression system in the shape of a sprinkler system, so that the impact of sprinklers on the ASET can be tested and the need for fire suppression when the objective is life safety of occupants can be determined. Sprinklers will be incorporated in the CFAST model, and upon activation of the sprinkler system, the HRR will remain constant. The fire suppression system will consist of standard response sprinklers with an RTI of 80 $m^{½}s^{½}$ and an activation temperature equal to 57°C.

As the sprinklers will have a spacing of maximum 4.6 m (circa value), the sprinkler heads will be placed maximum $\sqrt{\left(\frac{4.5\text{m}}{2}\right)^2+\left(\frac{4.5\text{m}}{2}\right)^2}\approx 3.3$ m away from the fire. The sprinkler head is placed as far from the fire as possible in order to achieve the highest activation time possible for the fire suppression system, constituting the worst case scenario.

3.6.1.4 Egress Provisions

As described in section 3.1, the ground floor is compartmentalized so that none of the two stores and the storage area in the back are connected to one another through doors. Therefore each of these areas will be provided with their own separate exits.

The storage area will have one exit only, while the two stores will be tried with two exits with varying widths.

3.6.2 Car Park & Offices

The basement levels and the upper floors will not be tried to the same extent as the retail space. The trial designs for the car park and office floors will be:

- Automatic detection systems;
- Fire suppression systems;
- Egress provisions.

The automatic detection system and fire suppression systems will have the same characteristics as described in 3.6.1.2 and 3.6.1.3. For the egress provisions, it will only be the widths of the doors and stairways that will be varied, while the number of exits will remain 1 for the car park levels and 2 for the office levels. The vehicle ramp in the basement will not be included in the calculations for evacuation time, and neither will the open stairway connecting L6 and L7.

3.7 Methodology

The evaluation analysis of the building has been carried out based on the suggested trial designs and the use of multiple computer programs and equations presented in this section.

3.7.1 RSET and Pathfinder

The RSET (Required Safe Egress Time) is calculated as:

$$RSET = t_d + t_n + t_{pre} + t_{evac} \quad (3.1)$$

Where:

$t_d =$ Time from ignition to detection of fire

$t_n =$ Time from detection of fire to notification of occupants (Notification time)

$t_{pre} =$ Time from notification to evacuation begins (Pre-movement time)

$t_{evac} =$ Time spent moving and queuing toward a place of safety (Evacuation time)

The detection and notification time depends on the type of detection (automatic or manual detection) and will be determined as described in section 3.6.1. The pre-movement time will be estimated based on the function of the room and the type and state of the occupants inside it.

In order to determine the evacuation time, Pathfinder software was applied to the building. Pathfinder is an agent based egress and human movement simulator, which provides graphical user interface for simulation design and execution as well as 2D and 3D visualization tools for result analysis [46]. It is able to simulate the evacuation movement of many occupants from large, complex building structures. Two different movement simulation modes are available in Pathfinder: Steering mode and SFPE mode.

Steering mode offers the most realistic looking movement, as it is dependent on collision avoidance and occupant interaction for the final result. Therefore Steering mode will also provide outcomes that are more similar to experimental data, resulting in faster evacuation times than those of the SFPE mode.

For the simulations being made in this study, the evacuation simulations will be performed in SFPE mode. SFPE mode utilizes the assumptions presented in the *SFPE Engineering Guide to Human Behavior in Fire* [47], meaning that simulation movement is controlled by door queues mainly, leading to outcomes that are similar to hand calculations. As for hand calculations based on the same set of SFPE assumptions, a boundary layer will be subtracted from the egress components, but in Pathfinder this boundary layer only applies to the door width as the door queue is the main controlling factor in the simulation. In hand calculations, boundary layers will also be subtracted from stairways and corridor widths provided that these act as the controlling components in the given situation.

Pathfinder allows the designer to assign velocities and pre-movement times to agents in the model as either constants, uniform distributions, normal distributions or log-normal distributions. It is also possible to assign different velocity/pre-movement time profiles to different groups of occupants as well as appointing specific exits for specific occupants to leave from.

The results of the simulation are presented in various reports (Summary report, door history, room history, occupants summary, occupant history) and in a 3D window, in which the evacuation process is shown graphically. Pathfinder enables the designer to get a complete view of the building and the pitfalls of the design of the building concerning the evacuation movement of occupants.

3.7.2 ASET and CFAST

The Available Safe Egress Time (ASET) will primarily be evaluated in a zone fire model called CFAST 7.2.0. CFAST stands for "The Consolidated Model of Fire and Smoke Transport" and is a two-zone fire model that predicts the thermal environment caused by a fire within a compartmented structure [48]. A fire compartment in a two-zone model consists of an upper smoke layer and a lower nonsmoke layer, and a fire will drive combustion products from the lower layer to the upper layer. The two layers have different characteristics, while the characteristics within one layer are uniform, their evolutions being described by a set of ordinary differential equations also known as the governing equations. These equations are derived from fundamental laws of mass and energy conservation, and as they are relatively simple, CFAST only requires a few tens of seconds of CPU time on a typical computer, unlike Computational Fluid Dynamics models. Two-zone models will predict temperature, species concentration, layer interface height, visibility and sprinkler/detector actuation among other characteristics.

In CFAST, several compartments can be built and connected to each other through horizontal and vertical vents. Various fires can be placed in different compartments with the main fire inputs being the heat release rate evolution, heat of combustion, chemical formula for the fuel, fire area and soot and CO yields. The compartments can be equipped with sprinklers, heat detectors, smoke detectors and mechanical ventilation.

Naturally, there are a number of limitations to zone fire models as they are comprised of relatively large, horizontal zones with uniform characteristics, which experimental measurements in fire compartments show deviations from. Also, entrainment into the plume, mixing at the soffit and any mixing between hot and cold layers must be modeled by formulas incorporated into the zone model, and these formulas may be inaccurate [49].

The ASET itself shall be determined based on the performance criteria developed in section 3.4, which dictate that the design of the building must meet the following tenability criteria:

a) A minimum smoke layer interface height of 2.2 m;
b) A maximum temperature of the lower layer of 45^{0}C;
c) A maximum temperature of the upper layer of 200^{0}C.

Thus, when any of these criteria have been exceeded, the ASET limit has been reached.

3.7.3 Fire Dynamics Simulator (FDS)

Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) model, also termed “field models” which are more sophisticated than zone models. While zone models such as CFAST divide the volume under consideration into a limited number zones, CFD models use a very large number of sub-volumes known as cells. For each of these cells, the basic laws of mass, momentum and energy conservation are applied. FDS is the most widely used CFD model for fire engineering, and it solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires [50]. FDS produces time-varying predictions of temperature, gas velocities, species concentrations etc. on each sub-volume, yielding spatially distributed results.

Input for an FDS model is more complicated to define than for a zone model and the simulation is more time-consuming. The output is also more difficult to treat, as it is more comprehensive than that of zone models. However, it can be used to solve more complex fire problems of turbulent flow, combustion chemistry, radiation, and mass, momentum and heat transfer at solid boundaries [51].

For this research, FDS was employed for two purposes: A comparison study for one of the design fires on the ground floor, which is documented in Appendix B, and for the modeling of the staircase shafts for the design fires on the upper floors, as CFAST appeared to yield incorrect results for the layer height for this matter. The smallest grid size applied was 100 mm, while the largest was 400 mm.

FDS does not provide lumped values for zones like CFAST, meaning that the smoke layer and temperatures are spatially distributed. Therefore, the FDS outcomes require more treatment than the CFAST outcomes, leading to mean values and standard deviations for FDS to be examined.

3.8 System Performance Evaluation

The performance-based design process is very flexible and iterative. Although the objectives and performance criteria have already been determined in previous sections, they can be re-evaluated if it is deemed that a higher level of safety is necessary after the first evaluation of design fires and trial designs. The framework for performance-based design identified by *the SFPE Engineering Guide to Performance-Based Fire Protection (2007)* [5] allows for these iterations when the selected design doesn't meet the performance criteria.

3.8.1 ASET/RSET Analysis for Retail Space

3.8.1.1 CFAST Model

An example of a calculation of the ASET in CFAST is provided in Appendix B. The entire ground story has been modeled in CFAST with all compartments as shown on Figure 3-16. Both stores are made up of their own compartments with no connections to any other compartments. The back of the building is also one compartment that is connected to the corridor compartment.

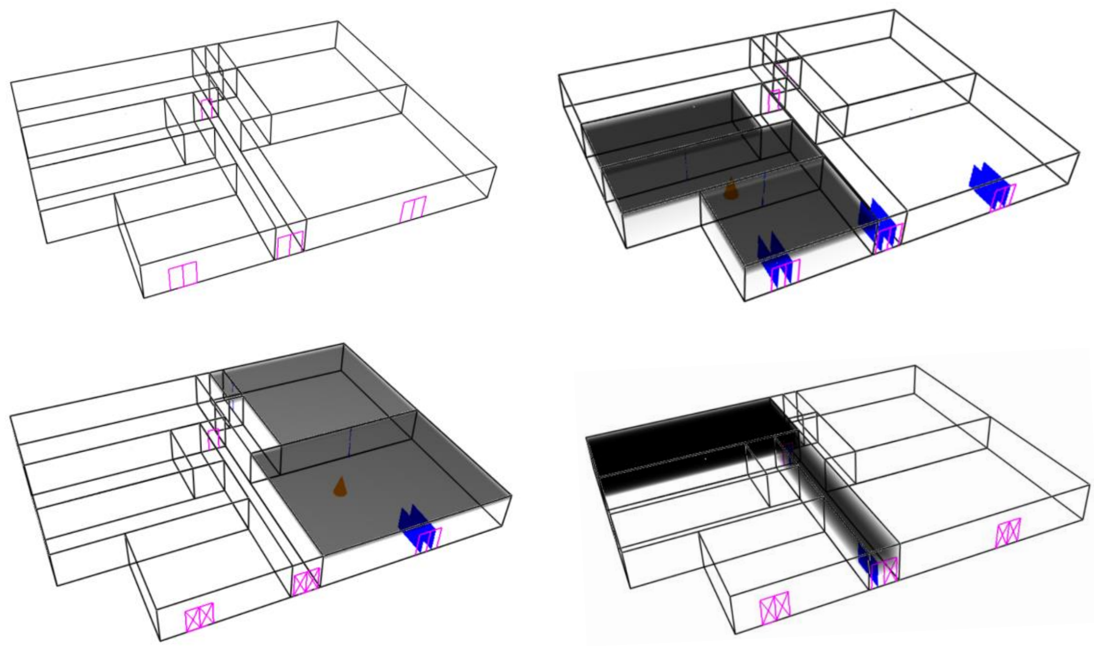


Figure 3-16: CFAST model of ground floor and smoke layer heights for different locations of the design fire at unspecified times.

The walls, floors and ceilings of the compartments are assigned to have characteristics equal to concrete. The characteristics are listed in Table 3-6.

The simulations were executed with one of the doors open in each shop. The door leading from the storage area to the corridor was modeled as open.

Material	Concrete
Specific heat [kJ/kg-K]	1.04
Conductivity [W/m-K]	1.8
Density [Kg/m^3]	2280
Emissivity	0.9
Thickness [m]	0.1

Table 3-6: Material characteristics for the compartment boundaries.

In order to ensure the safety level of the entire ground floor, the design fire was placed in different locations in separate simulations: In the smaller store, the larger store and the storage area in the back of the building.

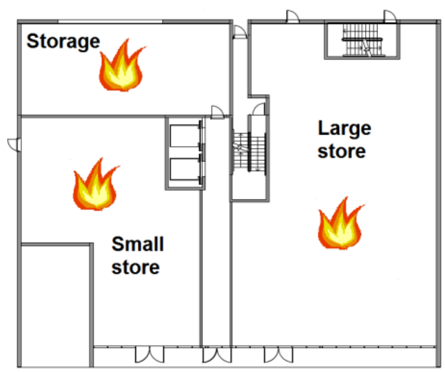


Figure 3-17: Locations of design fires

3.8.1.1.1 Design Fire Inputs

As described in section 3.4.1, the design fire shall have a fast fire growth rate $\left(\alpha = 0.101\ \frac{\text{kW}}{\text{s}^2}\right)$ and a peak HRR of 2700 kW. As the main goal of this performance based design is life safety of the occupants, the decay phase of the HRR evolution is not considered to be of importance when evaluating the performance criteria. The simulation will run for 700 s, resulting in the HRR plot shown in Figure 3-18.

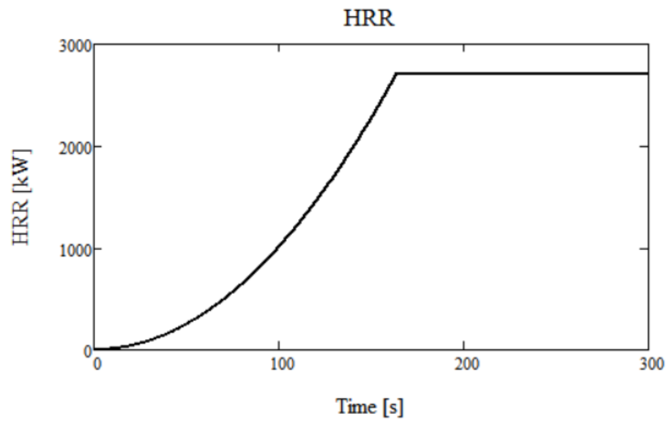


Figure 3-18: HRR evolution for the design fire in the retail space. The constant peak HRR continues throughout the 700 s long simulation.

The types of stores on the ground floor are not specified, making it difficult to determine the expected type of fuel in the space. Therefore four different types of materials, which can all be found in common stores, have been tested in order to find the most severe fuel type. Data from table A.39 and A.40 in the SFPE Handbook [52] for the four fuel types are listed in Table 3-7 below:

Material	**Polypropylene**	**Polystyrene**	**PMMA**	**Wood**
Chemical formula	C3H6	C8H8	C5H8O2	C6H12O6
Heat of combustion [MJ/kg]	43.3	39.7	25.2	13
Soot yield [g/g]	0.058	0.166	0.022	0.015
CO yield [g/g]	0.024	0.06	0.010	0.005

Table 3-7: Characteristics for different fuel types that will be tested in the CFAST model to determine the most conservative type of fuel for the design fire.

The evolution of the fire area (see Figure 3-19) was chosen conservatively and was maintained for all four types of fuel. The maximum fire area is 5 m^2, which will be reached when the peak HRR is reached.

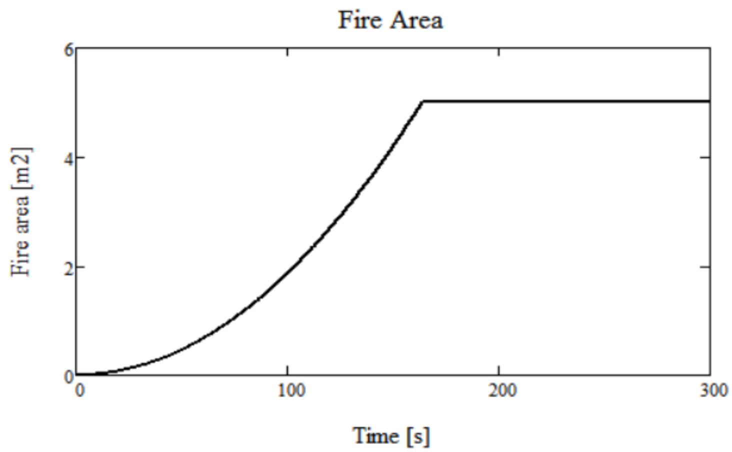


Figure 3-19: Evolution of fire area for the design fire. The peak area is 5 m^2.

The CFAST simulations showed that the four fuel types yielded very similar results concerning layer temperatures and smoke layer depths. However, as polystyrene showed slightly higher peak temperatures than the remaining fuels, polystyrene was chosen as the main fuel type on the ground floor.

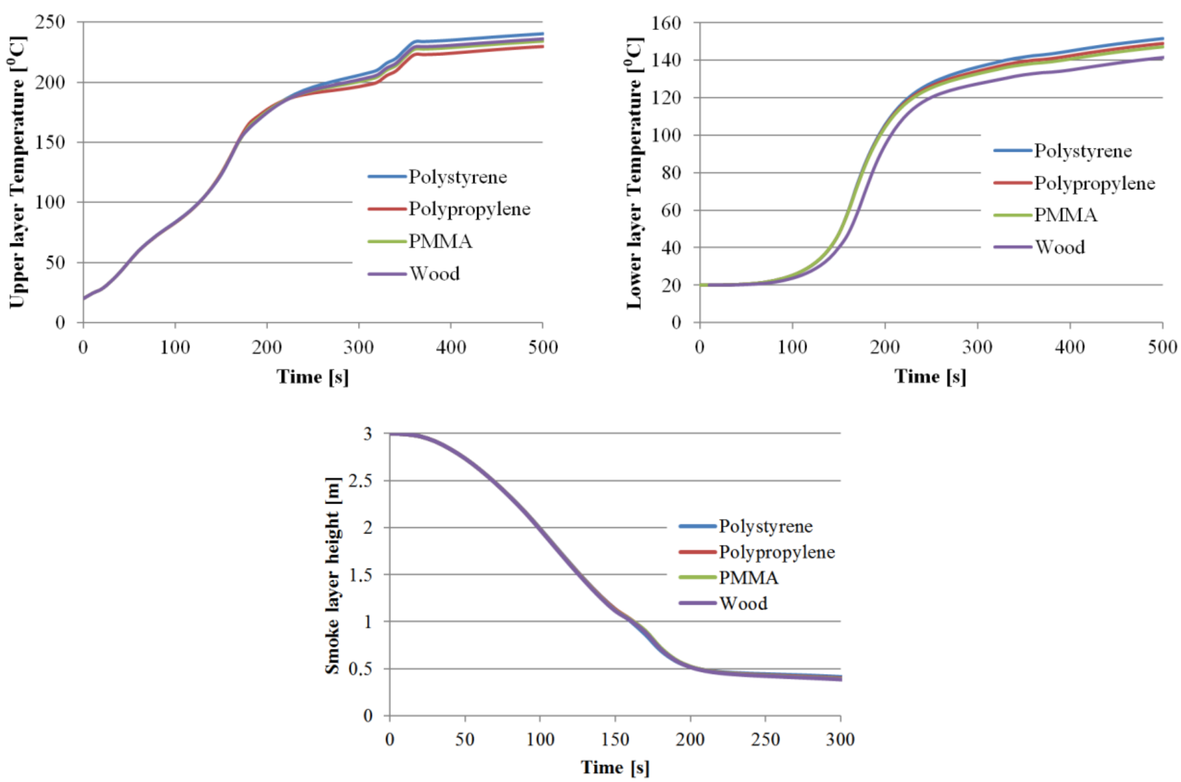


Figure 3-20: Severity of fuel types.

3.8.1.2 Detection & Pre-movement Time

The detection (including notification) time depends on the type of detection (automatic or manual) and will be determined as described in section 3.6.1.1 and 3.6.1.2. Manual detection is assumed to happen once the smoke layer height falls below 5% of the floor-to-ceiling height, which on the ground floor is equal to 2.85 m. According to CFAST, the smoke layer height in the small shop reaches this height after 40 s, resulting in a manual detection time of 40 s. The notification time is included in the 40 s. The automatic detection time is also calculated in CFAST as smoke detectors have been implemented in the model. The smoke detectors in CFAST will actuate when an obscuration level of 14%/m is reached, as described in section 3.6.1.2. This obscuration level leads to an automatic detection time (notification time included) of 18 s for the small shop.

The pre-movement time will be based on *A Study of Evacuation from Large Retail Stores* by Shields and Boyce [53]. The mean pre-movement time for the two stores shall be 29 sec, which is the mean of the all the mean pre-movement times measured in the study. The standard deviation (SD) shall be 16 sec for each of the stores, which is the mean standard deviation for the four stores examined in the study. The storage room in the back of the building will mainly be occupied by staff. Therefore the standard deviation will be reduced by half to 8 sec, while the mean pre-movement time of 29 sec will be maintained.

Manual detection + notification time [s]	40
Automatic detection + notification time [s]	18
Pre-movement time [s]	Mean = 29, SD = 22 (8 for storage)

Table 3-8: Detection and pre-movement times for the small shop

3.8.1.3 Evacuation Time

The evacuation time is found by human movement simulations in Pathfinder. All rooms on the ground floor have been modeled along with exits and occupants. The occupant density is set to 2.0 m^2/person and the average walking velocity is set to 1.17 m/s with a standard deviation of 0.22 m/s as defined in section 3.2. The pre-movement time of the occupants is incorporated into the Pathfinder model as normal distributions rather than constant mean values. Therefore the pre-movement time will be included in the evacuation time.

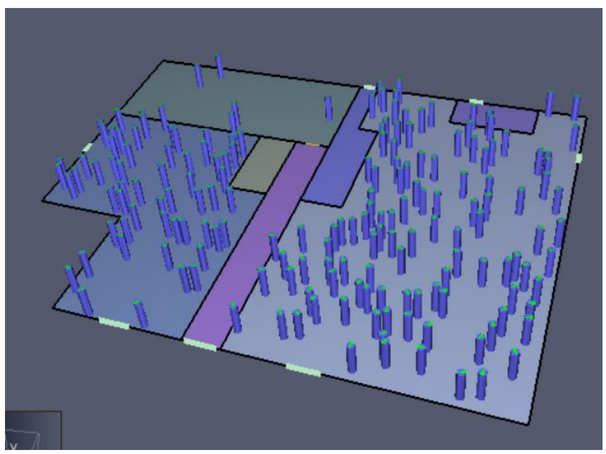


Figure 3-21: Screenshot of Pathfinder Evacuation Model

In order to optimize the widths of the exits, several simulations with varying door widths have been executed. In these simulations, the pre-movement time was kept at 0 sec so that the effect of the increasing door widths could be seen as the exits became wider. There are two exits in each store and both exits were increased at the same rate. The results are shown in Figure 3-22. As the exits become wider, the graphs flatten, which means that the queuing time by the exits is shortened. Therefore the evacuation time is controlled by the distance that the occupants have to walk to the exit rather than the time it will take to flow through the exit. When the doors in the small shop are 200 cm wide and the doors in large shop are 240 cm wide, the queuing time will be reduced significantly.

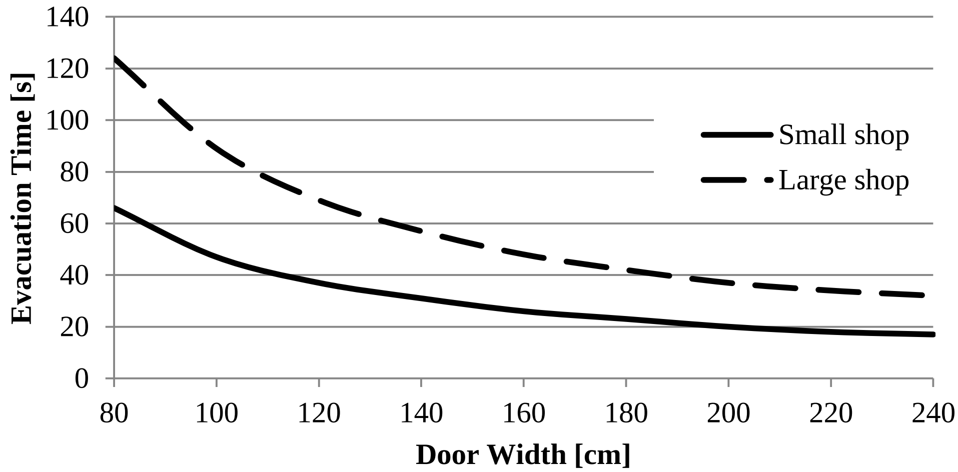


Figure 3-22: Evacuation times for the retail shops as dependent on exit widths.

The evacuation time will therefore depend more strongly on the velocity of the occupants. The evacuation process has been evaluated with varying velocities. The velocities shown in Table 3-9 are equal to the average velocity, and the average velocity +/- two standard deviations. The evacuation times have normal distributed pre-movement times included.

Velocity [m/s]	**0.73**	**1.17**	**1.61**
Evacuation time [sec] Small shop	74	67	63
Evacuation time [sec] Large shop	89	82	78

Table 3-9: Evacuation time for various constant velocities.

3.8.1.4 Evaluation of Trial Designs for Small Shop

The evaluation of trial designs will initially be conducted for the small shop solely, before the final design will be tried on both stores and the storage room. The results from section 3.8.1.2 and 3.8.1.3 for the upper and lower velocity values will be combined to the total RSETs for the small store.

Fire scenario	Trial design	Detection + Notification time	Pre-movement time + Evacuation time	RSET	ASET	ASET > RSET?
Left store	Manual detection, no sprinklers	40	74	114	88	NO
	Automatic detection system, no sprinklers	18		92	88	NO
	Automatic detection, sprinklers	18		92	88	NO

Table 3-10: RSETs and ASETs when the lower velocity fractile is used.

Fire scenario	Trial design	Detection + Notification time	Pre-movement time + Evacuation time	RSET	ASET	ASET > RSET?
Left store	Manual detection, no sprinklers	40	63	89	88	NO
	Automatic detection system, no sprinklers	18		70	88	YES
	Automatic detection, sprinklers	18		70	88	YES

Table 3-11: RSETs and ASETs when the upper velocity fractile is used.

The first evaluation of the trial designs shows that a manual detection system would not be adequate for any RSET. Therefore an automatic detection system is a necessity for the design of the story. It also showed that a fire suppression system in the form of sprinklers won't affect the ASET in any significant way as the sprinklers do not activate before after 75 sec.

3.8.1.5 Evaluation of Performance Criteria

The robustness of the performance criteria will have to be evaluated. If the smoke layer depth or the temperature increases rapidly, the criterion will not be fully robust as the environment will go from being completely safe to completely untenable in only a matter of seconds. Therefore the time evolution of the smoke layer interface height, the temperature of the upper layer and the temperature of the lower layer must be examined.

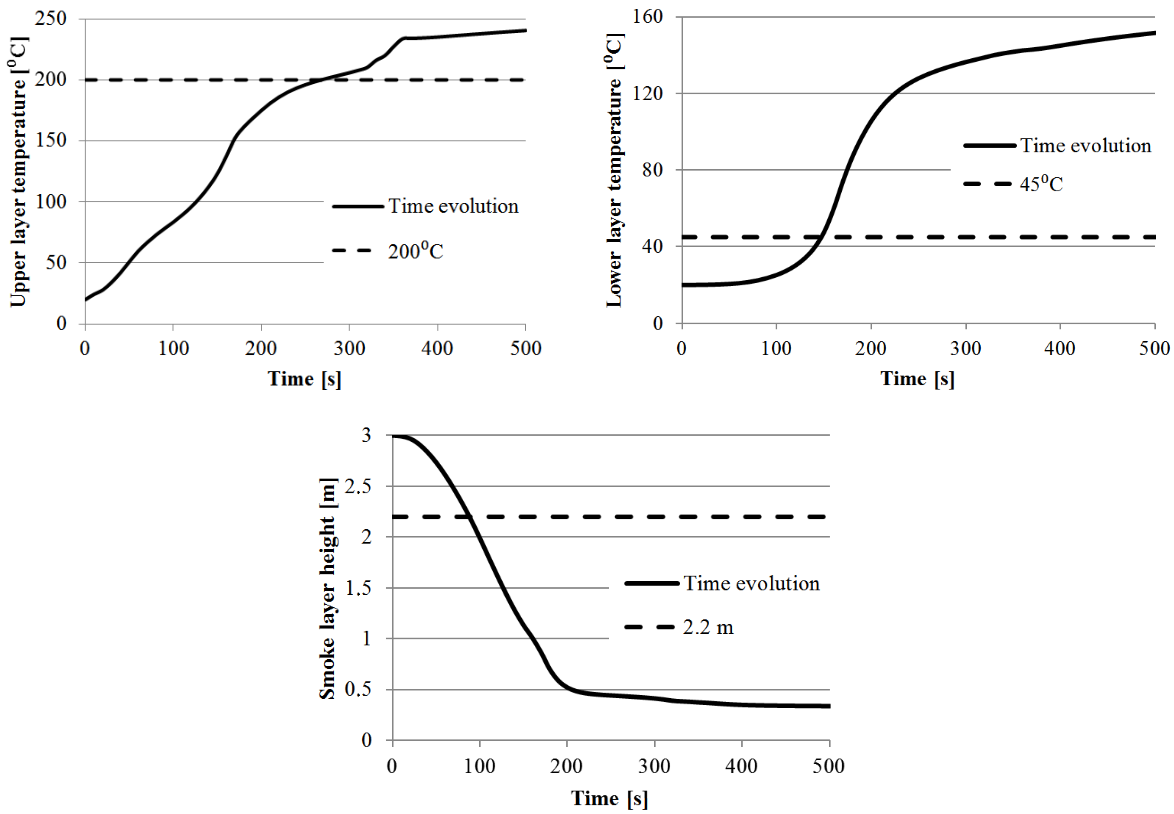


Figure 3-23: Time evolutions of smoke layer height and temperatures. The dashed lines indicate performance criteria limits.

As Figure 3-23 shows, the performance criteria are not considered adequately robust: The smoke layer interface height, the upper layer temperature and the lower layer temperature all have a very steep gradient in at the time that the ASET is exceeded. Therefore the criteria will have to be re-evaluated.

In order to assess the robustness of the smoke layer interface height and temperature criteria, the ASET as dependent on the criterion value will be examined for different values of the fire growth rate α, namely the initial growth rate +/- 10%. On the same figure, the upper and lower values for the RSET (for the upper and lower fractiles of the occupant velocity) will be plotted.

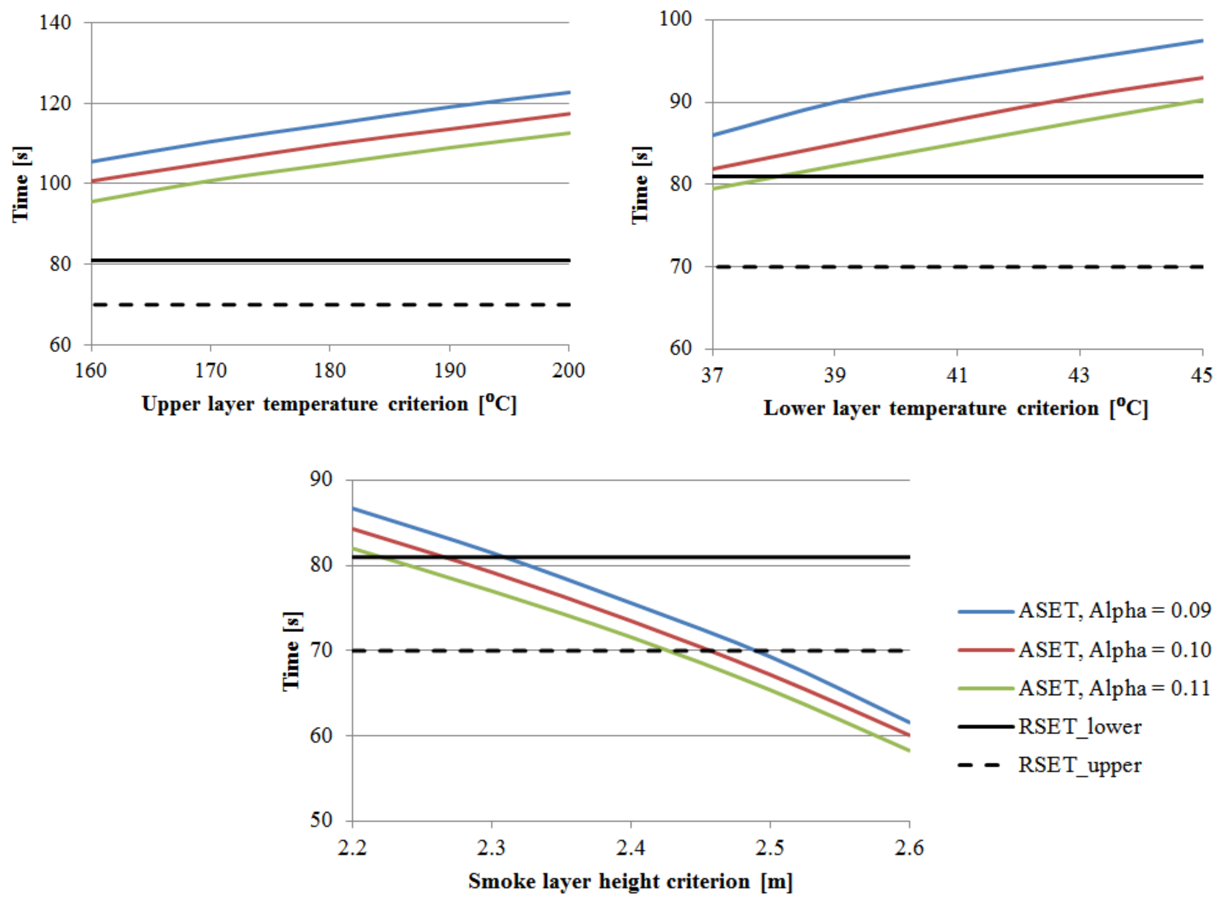


Figure 3-24: ASETs vs. RSETs for the small shop for each performance criterion. RSET_upper and RSET_lower indicate the RSETs for the upper and lower velocity fractiles, while the ASETs represent various growth rates.

Firstly, Figure 3-24 shows that the controlling criterion is the smoke layer interface height as the RSETs is well below any ASET for the temperature criteria. Secondly, the plots show that the smoke layer criterion fundamentally isn't robust enough as the RSETs intersect with the ASETs for the smoke layer heights.

To solve the robustness issue, either the ASET must be raised or the RSET lowered. A method to do this is to further refine the inputs used when computing the ASET/RSET such as the fire growth rate. Therefore the choice of a fire growth rate value of 0.101 kW/s^2 was further investigated by researching other papers defining fire growth rates for retail spaces. D. Wang et al. [54] define the design fire for retail areas as having a medium fire growth rate and little casualty, while M. Nilsson et al. [55] utilize an α-value ranked between a medium and a fast fire growth rate. The paper that was originally used to identify the fire growth rate [39] refers to a study completed by Wright and Archer, which categorized occupancies in accordance with a linear fire growth rate, also placing retail occupancies in the medium fire growth rate category. Based upon these studies and the fact that the original paper characterized the fast fire growth rate as the 95%-fractile, making it a conservative value, a fire growth rate of 0.101 kW/s^2 will be considered a sufficient deterministic value. However, as Figure 3-25 shows, further refinement of the inputs is still needed in order to achieve a satisfactory level of robustness for the ground story design.

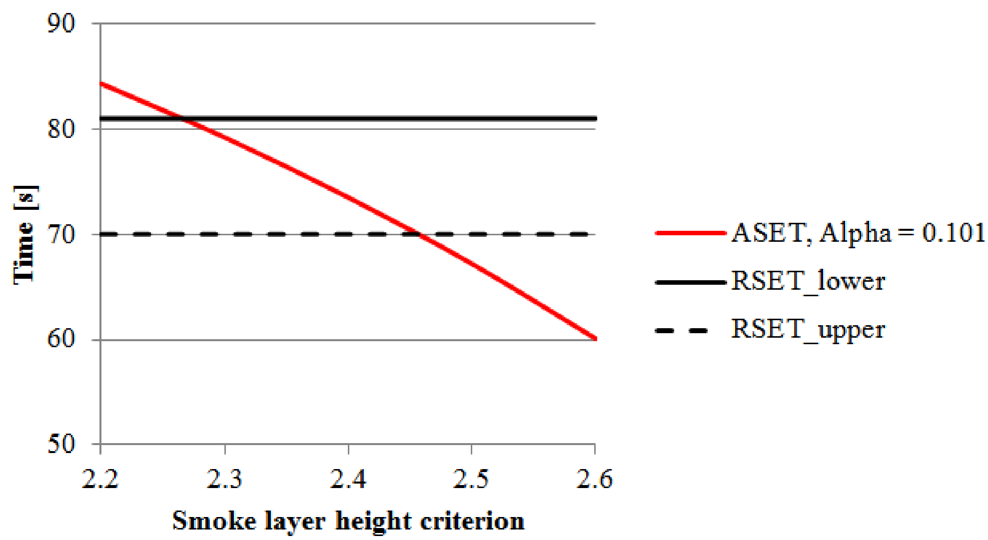


Figure 3-25: ASET vs. RSETs for the small shop for the layer height criterion. RSET_upper and RSET_lower indicate the RSETs for the upper and lower velocity fractiles. The shown ASET is determined by the initial fire growth rate of 0.101 kW/s^2.

The pre-movement time should also be re-evaluated. Initially, the pre-movement time was incorporated into the Pathfinder model as a normal distribution and the RSET was only varied for different occupant velocities. Instead the effects of the velocity and pre-movement time distributions will be examined in separate plots. For this purpose, Figure 3-26 and Figure 3-27 have been created as they illustrate the RSETs generated from the mean velocity and pre-movement time and how it varies with their standard deviations.

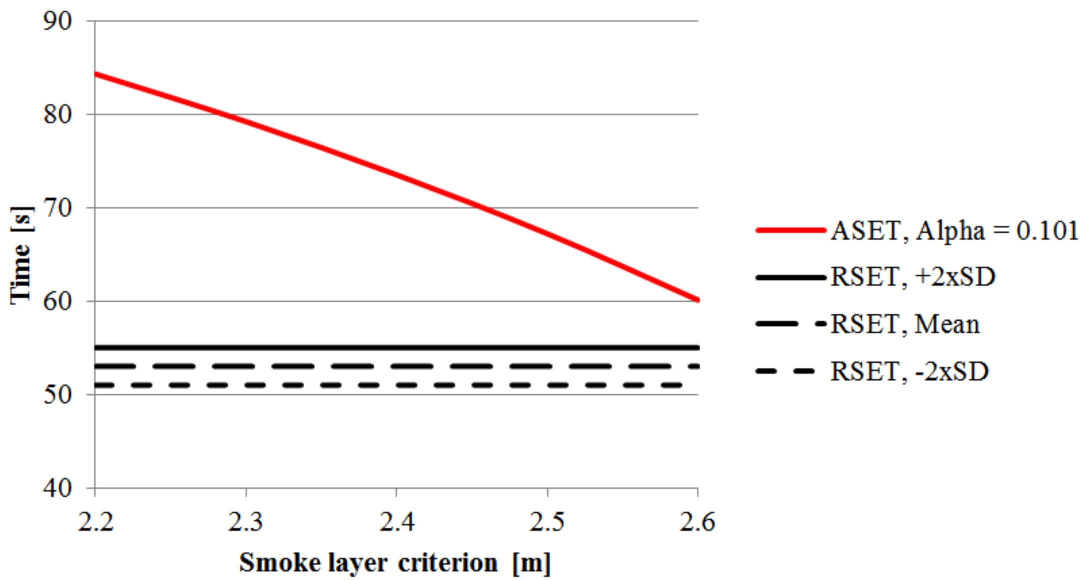


Figure 3-26: RSETs vs. ASET for varied occupant velocity and mean pre-movement time. Alpha = fire growth rate. SD = Standard Deviation.

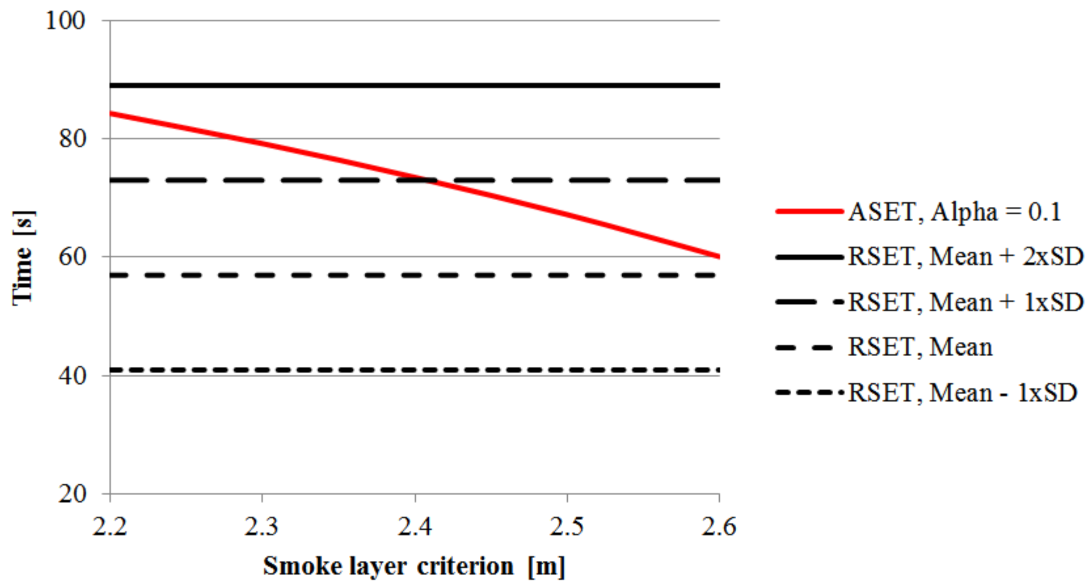


Figure 3-27: RSETs vs. ASET for varied pre-movement time and mean occupant velocity. Alpha = fire growth rate. SD = Standard Deviation.

Figure 3-26 and Figure 3-27 show that the main controlling factor is the pre-movement time as its range is much broader than the one of the velocity.

3.8.1.6 Re-evaluating Trial Designs

The analysis performed show that the initial trial designs don't provide an adequate level of robustness. Therefore new suggestions to the design of the building are necessary. There are two variables that can be adjusted:

a) The ceiling height;
b) The pre-movement time.

Increasing the Ceiling Height

Because the controlling performance criterion is the smoke layer interface height, increasing the floor-to-ceiling height is an effective means to meet the performance criteria. When the ceiling height is increased, the ASET will also be increased. Figure 3-28 features the ASET for ceiling heights of 3.00, 3.25 and 3.50 m as dependent on the smoke layer criteria. The RSETs for the various pre-movement times are also included.

The analysis indicates that the ceiling will have to be increased from 3.0 m to 3.5 m in order to provide a sufficiently robust system. A 3.5 m high ceiling will allow 95 % of the occupants to evacuate before the smoke layer falls below 2.4 m, providing the remaining occupants with a time buffer to escape within from all compartments.

Reducing the Pre-movement Time

In retail areas, the critical pre-movement times originate from activities such as costumers putting clothes on in dressing rooms or finding a safe space for items that they collected, so that they can go back and find them later.

Therefore another option is to train the staff in the stores in fire safety management, enabling them to instruct other occupants in the stores to evacuate immediately upon detection of the fire. This would significantly reduce the pre-movement time, increasing the distance between the ASET and the RSET plot lines. The actual effect on the pre-movement time when occupants are being prompted by staff to evacuate cannot be determined deterministically as research in this area is very limited. Instead it is estimated that the achieved level of fire safety and robustness of the building is equal to the one that is attained when increasing the ceiling height to 3.5 m.

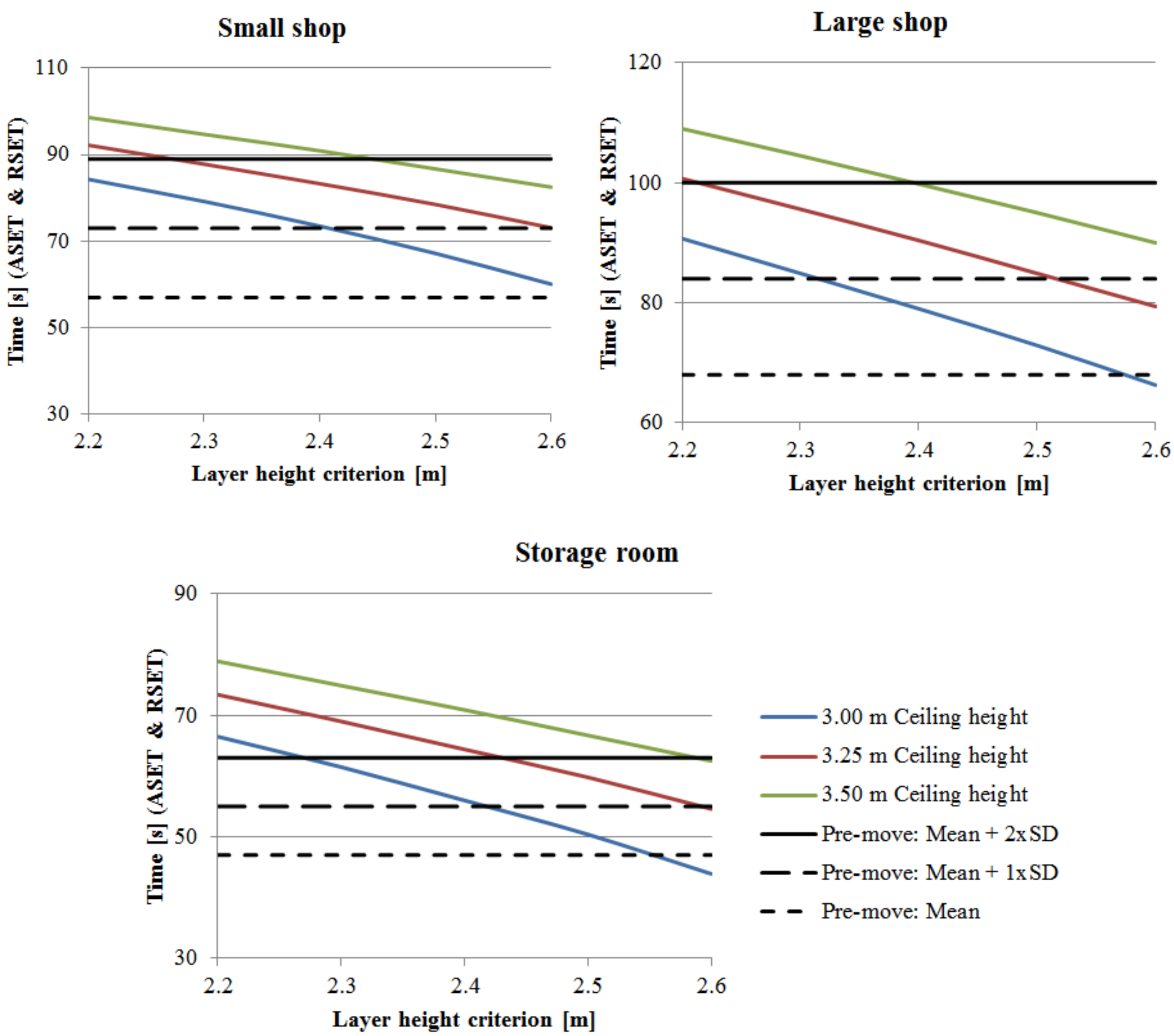


Figure 3-28: RSETs vs. ASETs for the different design fires in the office area. The RSETs (black lines) are based on various pre-movement times, while the ASETs (colored lines) depend on the ceiling height. The occupants move with mean velocity.

3.8.2 ASET/RSET Analysis for Office Floors (L1-L7)

3.8.2.1 CFAST Model

One regular office level was modeled in CFAST. Reduced versions of the staircases were modeled as well. The fire is located centrally by the front of the office space, from where the smoke will spread throughout the space before exiting through the open stairway doors. This will eventually lead to the staircases becoming untenable, which will be examined in FDS. In CFAST, an ASET for the office space will be determined.

The doors leading to the meeting rooms are also assumed open.

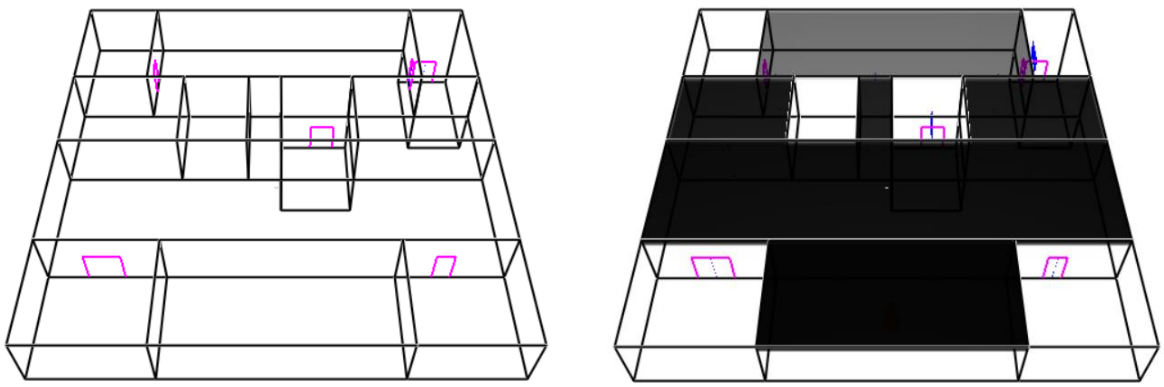


Figure 3-29: CFAST model for a regular office floor. The smoke distribution at an unspecified time is shown to the right. Doors are assumed open.

The walls, floors and ceilings of the elevator and staircase compartments are assigned to have characteristics equal to concrete. The outer walls are defined as glass. The characteristics are listed in Table 3-12.

Material	**Concrete**	**Glass**
Specific heat [kJ/kg-K]	1.04	0.84
Conductivity [W/m-K]	1.8	1.05
Density [Kg/m^3]	2280	2500
Emissivity	0.9	0.9
Thickness [m]	0.1	0.02

Table 3-12: CFAST material characteristics for the compartment boundaries on the office floors.

3.8.2.1.1 *Design Fire Inputs*

Three different fire scenarios will be executed for the upper floors. These scenarios include severe fires originating in:

- Regular office furniture (desks, papers etc.);
- A sofa;
- Library content (shelves, books, etc).

The characteristics for the design fires are described in section 3.5.2 for the office design fires and section 3.5.4 for design fires in the library. These characteristics are listed in Table 3-13.

Design Fire	**Office furniture**	**Sofa**	**Library content**
Fire growth rate [kW/s^2]	0.016 (medium)	0.1055 (fast)	0.047 (fast)
Peak HRR [kW]	3000	3000	2375
Material	Wood/paper	Polyurethane	Wood/paper
Chemical formula	$C_6H_{10}O_5$	$C_{25}H_{42}N_2O_6$	$C_6H_{10}O_5$
Heat of Combustion [MJ/kg]	18.0	23.0	18.0
Soot yield [g/g]	0.015	0.200	0.015
CO yield [g/g]	0.005	0.050	0.005

Table 3-13: Design fire characteristics for the different fuel types on of office floors.

As the main goal of this performance based design is life safety of the occupants, the decay phase of the HRR evolution is not considered to be of importance when evaluating the performance criteria. The HRR plot is shown on Figure 3-30.

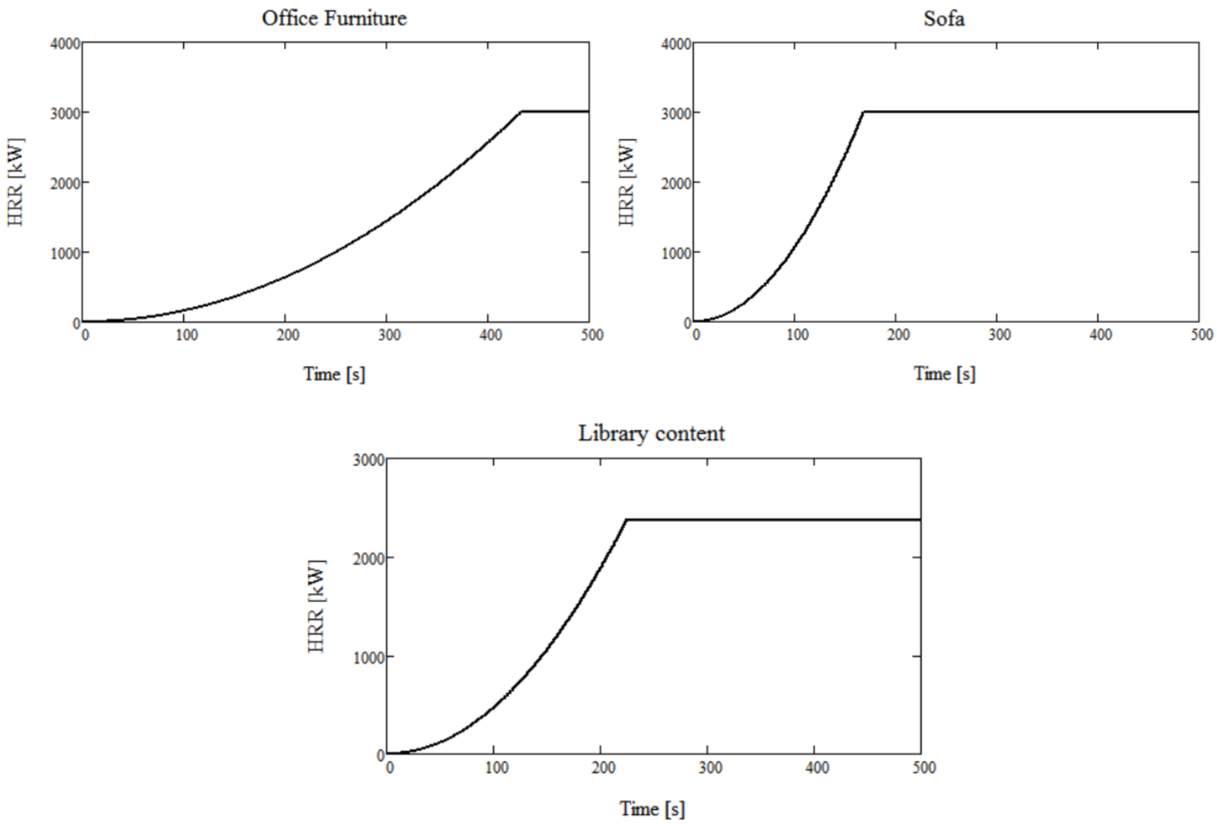


Figure 3-30: HRR evolutions for the different fuel types on the office floors.

The maximum fire area was chosen to be 3 m^2 for all three fires. The fire area curves will have the same shape as the HRR plots, reaching the 3 m^3 at the same time as the peak HRR is reached, remaining constant from that point.

3.8.2.2 FDS Model - Staircases

An FDS model has been created in order to calculate the ASET for the staircases on the upper floors. In FDS, only the sofa fire scenario was examined as this would lead to the most severe ASET. The tenability conditions in the staircase will have to be below the performance criteria limits for as long as the occupants are evacuating the office floor, for only in this period will the doors be assumed open.

Characteristics for materials are listed in Table 3-14. The model consists of:

- All floor/ceiling surfaces: Concrete;
- Walls surrounding the staircases and elevator: Concrete;
- Outer walls: Glass;
- Walls surrounding meeting rooms: Plasterboard

Material	**Concrete**	**Glass**	**Plasterboard**
Specific heat [kJ/kg-K]	1.04	0.84	0.84
Conductivity [W/m-K]	1.8	1.05	0.48
Density [Kg/m^3]	2280	2500	1440
Emissivity	0.9	0.9	0.9
Thickness [m]	0.1	0.02	0.02

Table 3-14: FDS material characteristics for the compartment boundaries on the office floors.

The base of the fire is made of polyurethane with characteristics as in Table 3-13 for the sofa fire. There is a space of 1.0 m between the outer walls and the boundaries of the mesh. The mesh boundaries outside the building as well as the door openings at the bottom of the staircases have been designed as open surfaces. There are no openings in the outer walls of the building.

The pressurization of the staircases is modeled by four vents that release a mass flux of 8 kg/s of air each. To account for all effects of the pressure, the FDS model contains three stories, as the fire strategy calls for three floors to evacuate when a fire is detected.

There are three different grid sizes in the model:

- 10 x 10 x 10 cm: Around the fire and in the staircases on the fire floor;
- 20 x 20 x 20 cm: The remaining volume of the fire floor;
- 40 x 40 x 40 cm: The two lower floors and the lower parts of the staircases.

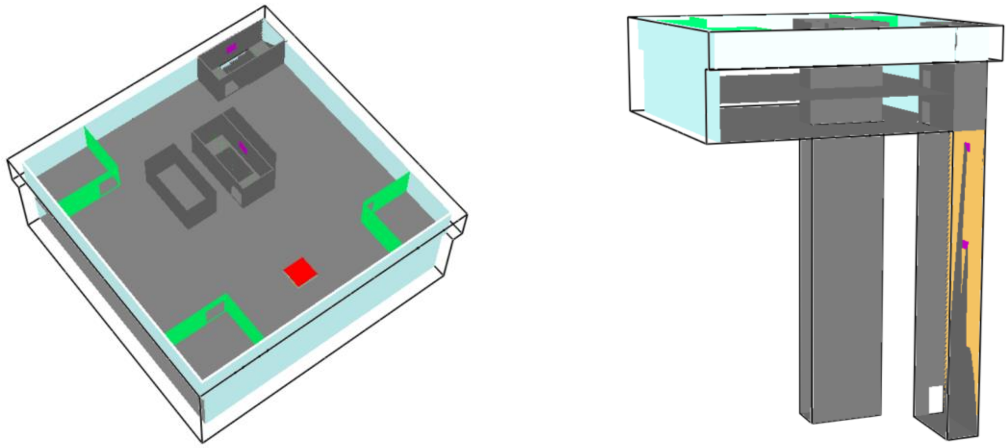


Figure 3-31: Screenshot of FDS model.

The layer heights and upper and lower temperatures will be measured with 40 layer zoning devices in each of the staircases. The devices have been evenly distributed with heights equal to floor-to-ceiling heights of the top floor. The values will therefore be spatially distributed throughout the top of the staircase compartment.

The HRRPUA is set to 1000 kW/m^2, which for a maximum fire area of 3 m^2 results in a peak HRR of 3000 kW. The flame spread rate is set to 5.7 mm/s in order to produce a similar HRR shape as those applied in the CFAST model. The HRR produced by the FDS simulation is shown in Figure 3-32. The evolution of the smoke layer is visualized in Figure 3-33 and Figure 3-34.

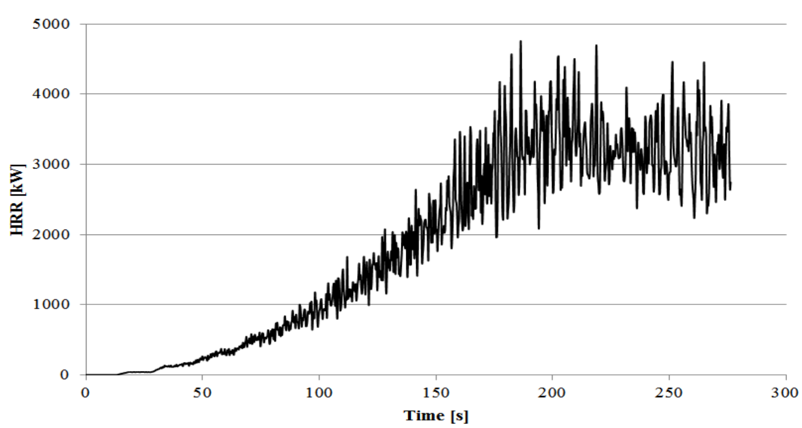


Figure 3-32: HRR output produced by FDS.

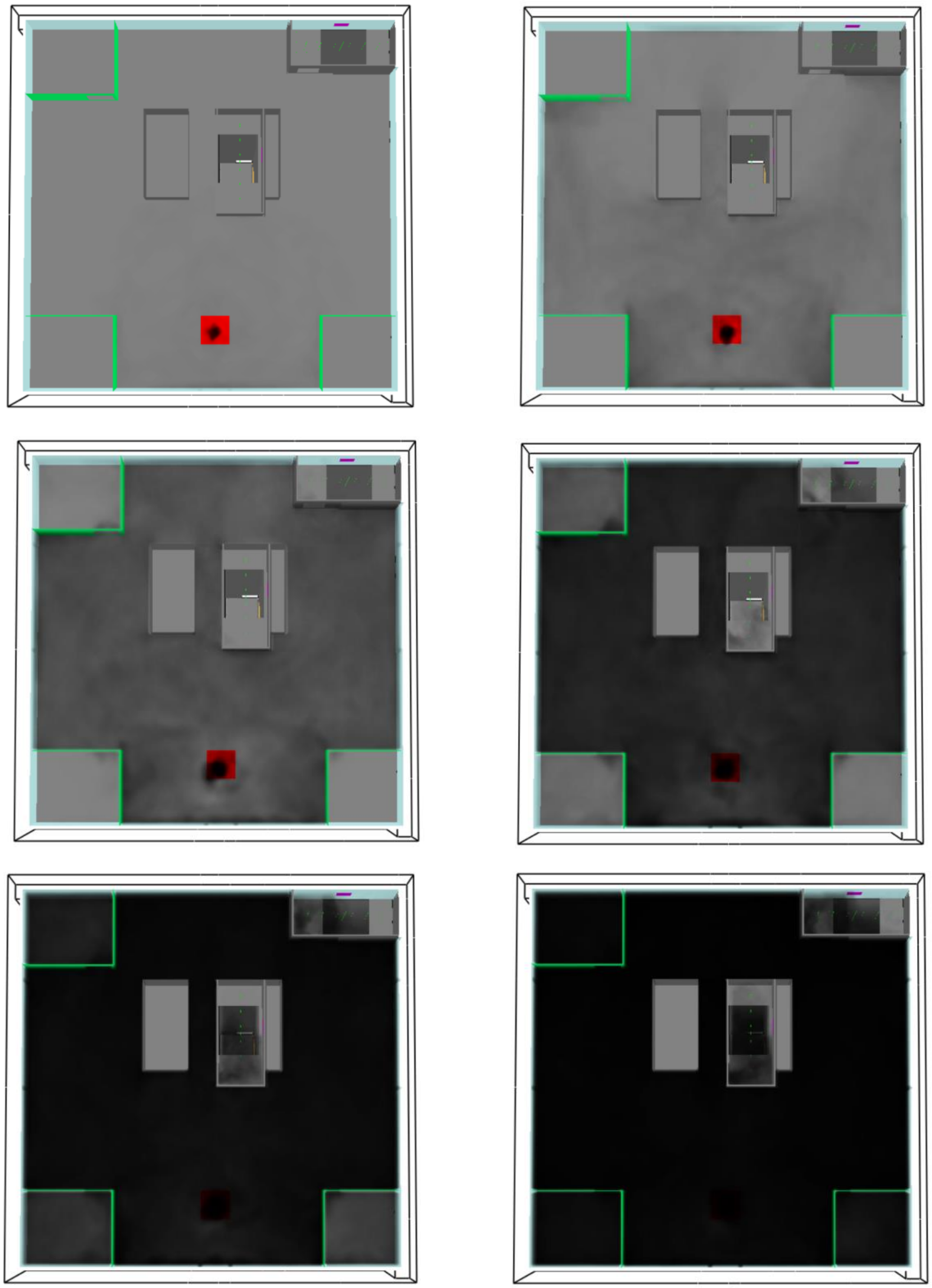


Figure 3-33: Smoke evolution in the FDS office model, seen from the top.

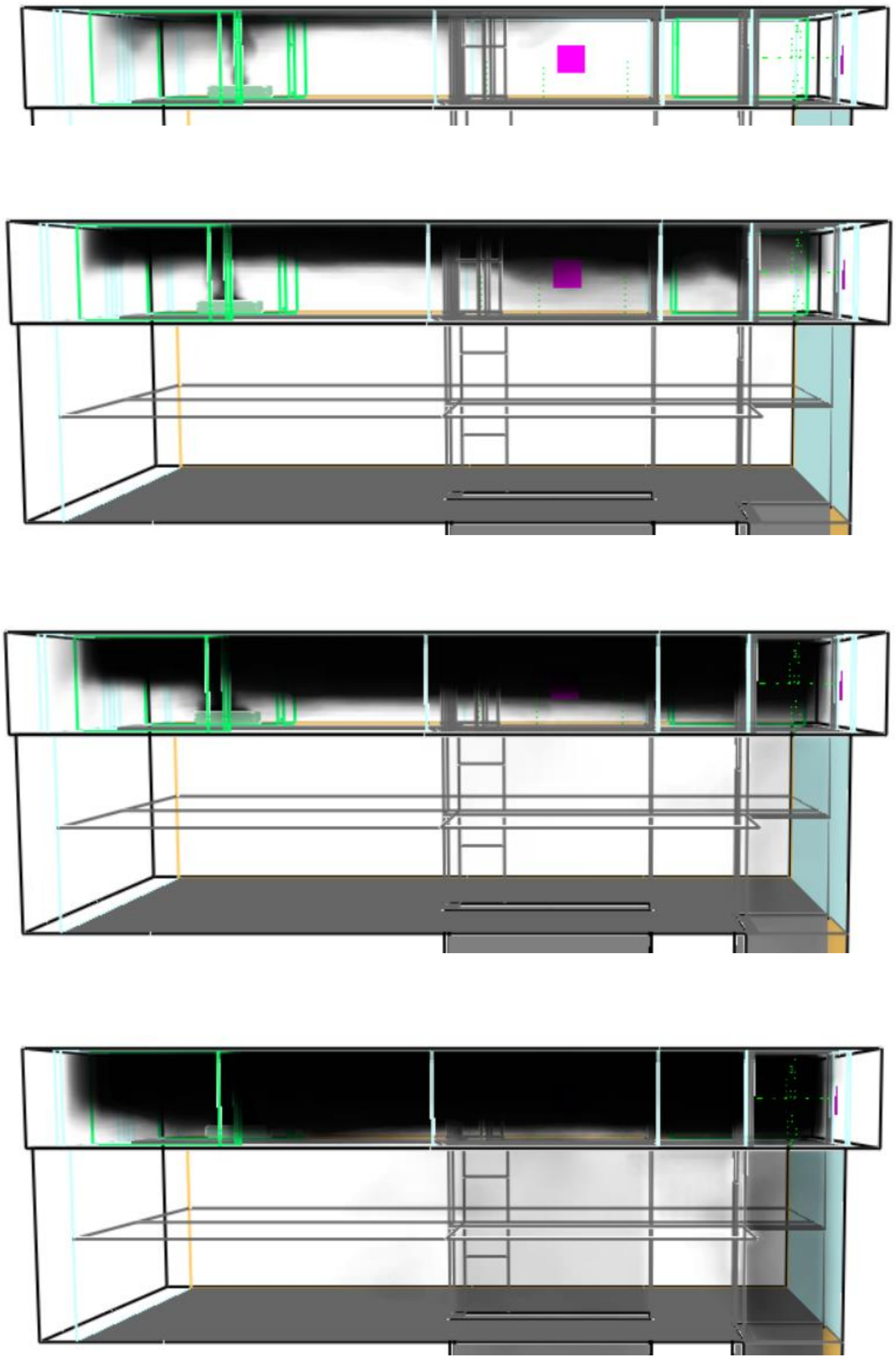


Figure 3-34: Smoke evolution in the FDS office model, seen form the side.

3.8.2.3 Detection & Pre-movement Time

The detection times were calculated in CFAST. The maximum detection times for the three scenarios were as follows:

- Office furniture: 67 s;
- Sofa: 26 s;
- Library: 45 s.

For the pre-movement time, the study *Evacuation Time and Movement in Office Buildings* by Proulx et al. was used as foundation [56]. Based on this study, it is assumed that:

- After 15 s, 15 % of occupants will have initiated evacuation;
- After 30 s, 45 % of occupants will have initiated evacuation;
- After 45 s, 75 % of occupants will have initiated evacuation;
- After 60 s, 90 % of occupants will have initiated evacuation.

These pre-movement times are valid for the occupants on the fire floor. For occupants in adjacent compartments, 30 s will be added to the listed pre-movement times.

3.8.2.4 Evacuation Time

Because the fire strategy requires that occupants on the fire floor plus the floor above and below all evacuate when a fire is detected, all three floors have been modeled in Pathfinder. The 30 s extra pre-movement time for the occupant on the upper and lower floor are included in the evacuation time, meaning that the agents will start evacuation 30 s later than the agents on the fire floor.

The occupant density is set to 6.0 m^2 and the average walking velocity is set to 1.17 m/s with a standard deviation of 0.22 m/s as defined in section 3.2. The normal distribution of the velocity is therefore included in the total evacuation time.

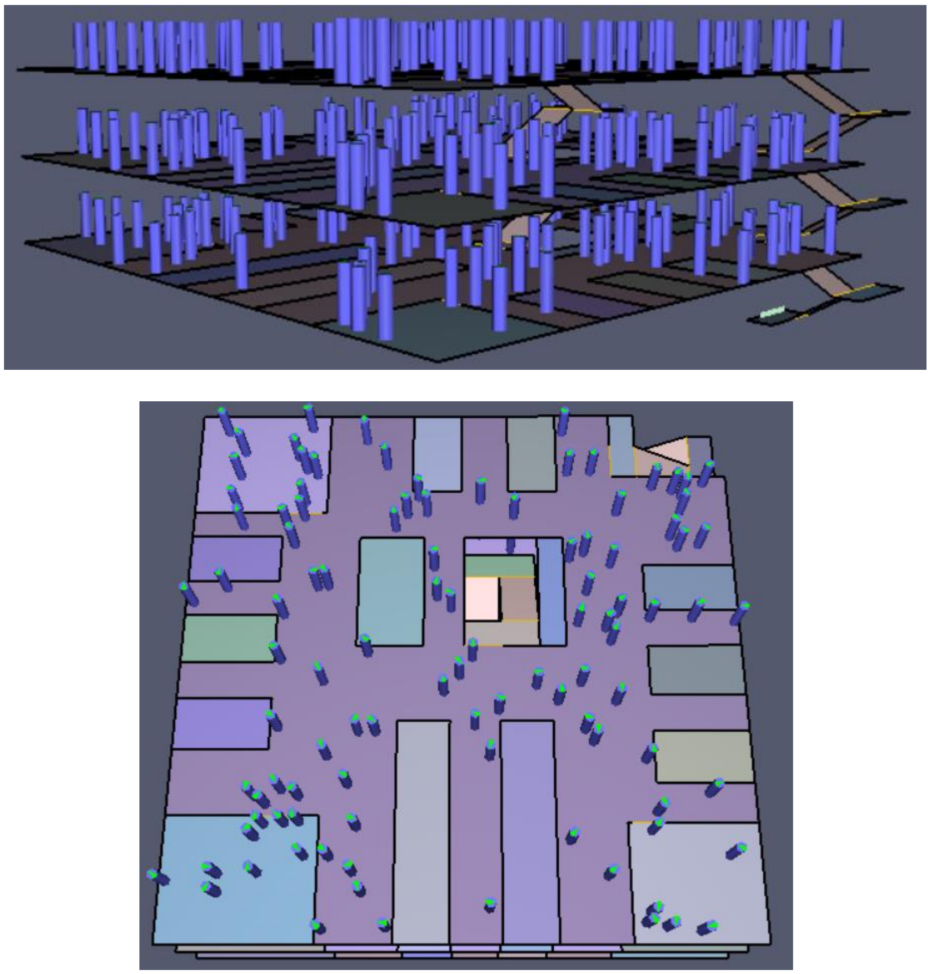


Figure 3-35: Screenshots of Pathfinder Evacuation Model, office floors.

Figure 3-36 shows the evacuation time as a function of the exit width, both doors and stairways.

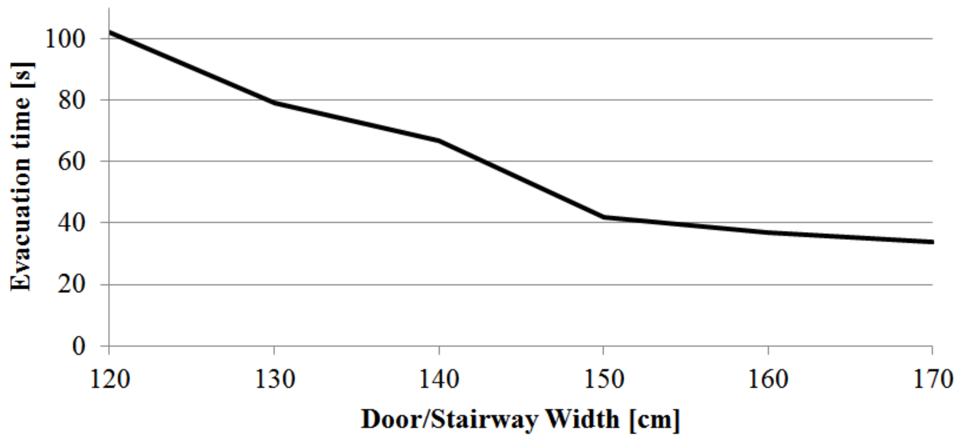


Figure 3-36: Evacuation time as dependent on the exit widths for the office area.

Based on the data visualized on Figure 3-36, a door and stairway width of 1.60 m will be maintained. The evacuation time listed in Table 3-15 does not include pre-movement time for occupants on the fire floor. The velocities were normal distributed in Pathfinder.

Velocity [m/s]	**0.5 – 1.7**
Evacuation time [sec] Office area	37

Table 3-15: Evacuation time for the office floor for exit widths = 160 cm.

3.8.2.5 Evaluation of Trial Designs

Fire scenario	Trial design	Detection + Notification time	Pre-movement time	Evacuation time	RSET	ASET	ASET > RSET?
Office furniture	Automatic detection system, no sprinklers	67	60	37	164	185	YES
	Automatic detection, sprinklers					185	YES
Sofa	Automatic detection system, no sprinklers	26	60	37	123	115	NO
	Automatic detection, sprinklers					115	NO
Library content	Automatic detection system, no sprinklers	45	60	37	142	140	NO
	Automatic detection, sprinklers					140	NO

Table 3-16: ASETs and RSETs for the various design fire scenarios. The pre-movement time is the 90 percentage fractile. The velocity is normal distributed.

The first evaluation of the trial designs shows that the design of the office floors is inadequate as the RSET exceed the ASET in some cases. It also showed that a fire suppression system in the form of sprinklers does not affect the ASET as the sprinklers do not actuate until:

- 187 s for the sofa design fire;
- 239 s for the library design fire;
- 315 s for office design fire.

The criterion to be exceeded first in the staircases was the layer height criterion in the corner staircase. The mean smoke layer height fell below 2.2 m after 170 s for the sofa design fire, which is above the RSET for the office area, and therefore the fire doors will have closed before the ASET in the staircase is reached.

3.8.2.6 Evaluation of Performance Criteria

The performance criteria have been evaluated for the sofa design fire as this is the most severe scenario. The criterion for the upper layer temperature is considered robust due to the flat rate of increase after the 200°C is exceeded. The lower layer temperature and layer height criteria are less robust because of the rapid rates of increase/decrease. Since the layer height is the controlling element in all the cases, only this criterion will be reevaluated.

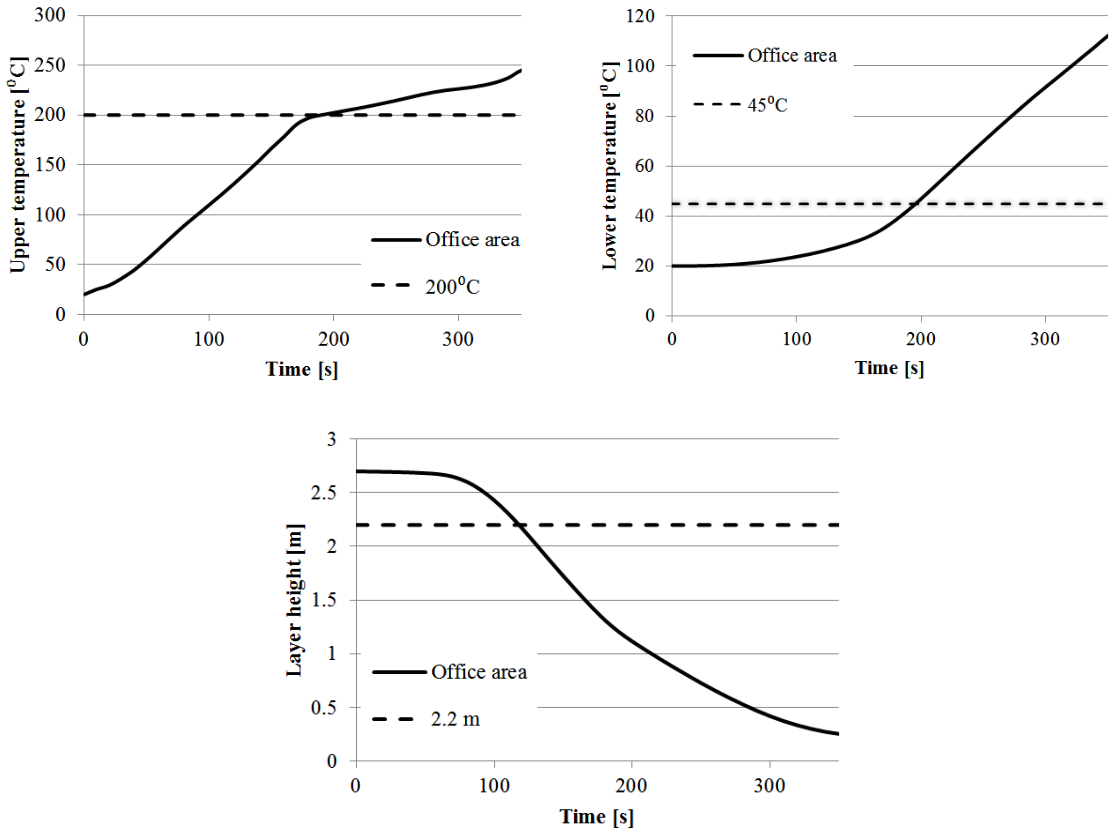


Figure 3-37: Time evolutions of smoke layer height and temperatures for the sofa fire scenario. The dashed lines indicate performance criteria limits.

Because the temperatures measured in the staircases were not severe, only the spatially distributed values for the layer heights in the staircase must be examined as well. This will be done by means of standard deviations.

3.8.2.7 Re-evaluating Trial Designs

It has been determined that the design of the office floors in the building is not sufficiently fire safe. It has also been determined that a fire suppression system won't affect the ASET and that optimization of the clear widths of the exits has already been achieved. As an alternative solution to decrease the ASET, the ceiling height of the upper floors has been increased. The results have been compared with RSETs for different levels of pre-movement time (the times for which 90%, 75% and 45% have initiated evacuation). The outcomes are shown in Figure 3-38.

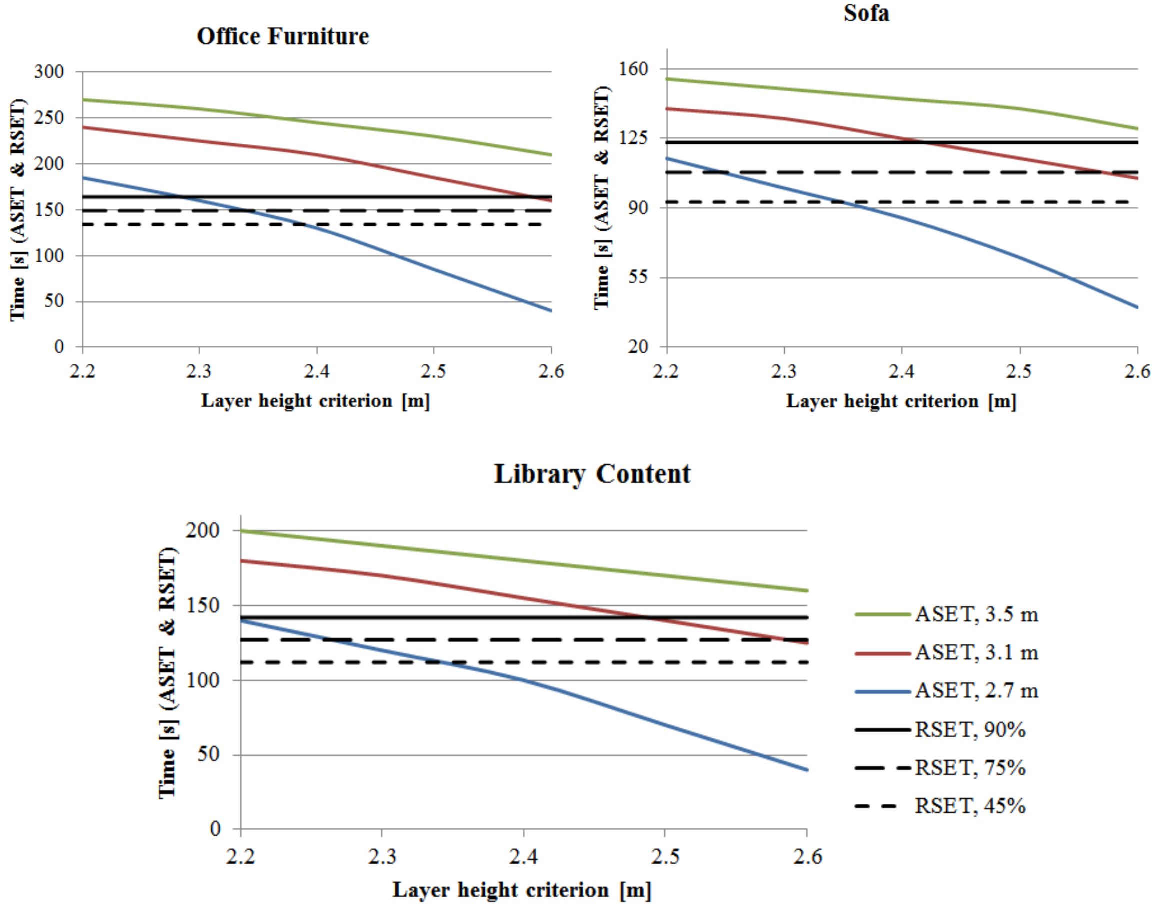


Figure 3-38: RSETs vs. ASETs for the different design fire scenarios. The RSETs (black lines) are based on various pre-movement times, while the ASETs (colored lines) depend on the ceiling height.

Based on the outcomes, an adequate level of fire safety can be achieved by either:

- Increasing the ceiling height from 2.7 m to 3.1 m;
- Increasing the ceiling height from 2.7 m to 2.9 m and providing appropriate staff with fire safety training, thus decreasing the pre-movement time.

When the ceiling height is raised to 3.1 m, 90% of occupants will most likely have evacuated the building, while a safety buffer is still available for the remaining 10%.

Also, instructing appropriate staff, such as supervisors, with fire safety training, teaching them how to orchestrate evacuation of employees, a reduction of the pre-movement time can be assumed. This way, the 90% limit can be pushed down to the 75% limit, allowing for a smaller ceiling height increase to only 2.9 m.

3.8.2.7.1 Layer Height in Staircases

The layer height evolution in the cases of 3.1 m and 2.9 m floor-to-ceiling heights are depicted in Figure 3-39 and Figure 3-40 respectively. The plots include the mean layer height in the staircase and the mean layer height plus two standard deviations. The figures indicate that for a ceiling height of 3.1 m and 2.9 m, 95 % of the layer zoning devices measure a layer height above 2.2 m until 170 s and 141 s respectively. The maximum RSET for a 60 s pre-movement time was 135, which both ASETs in the staircase exceed.

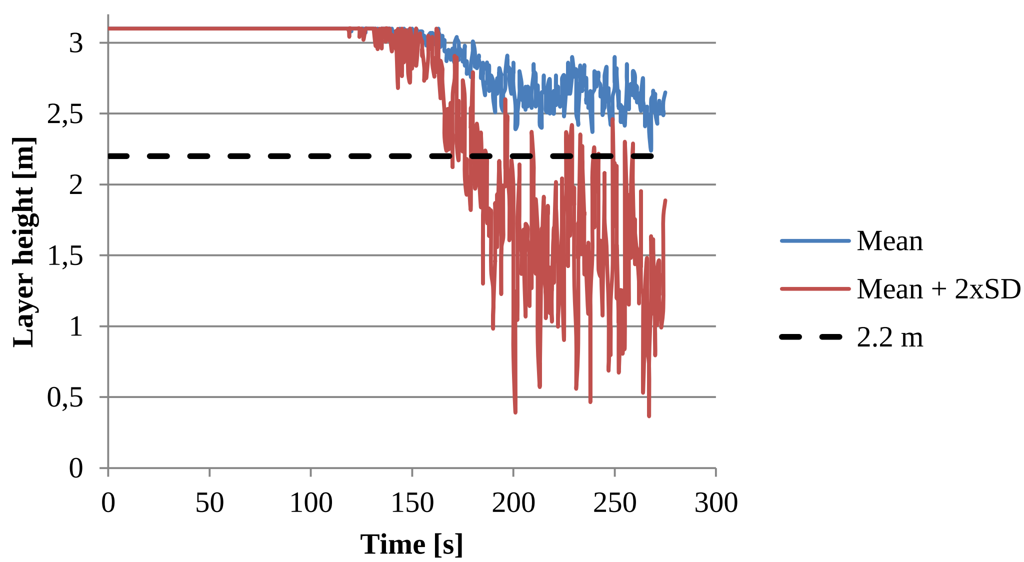


Figure 3-39: Layer height evolution in the staircase, when the ceiling height is 3.1 m. The FDS outcomes are spatially distributed, so the mean layer height and the mean layer height plus two standard deviations are specified.

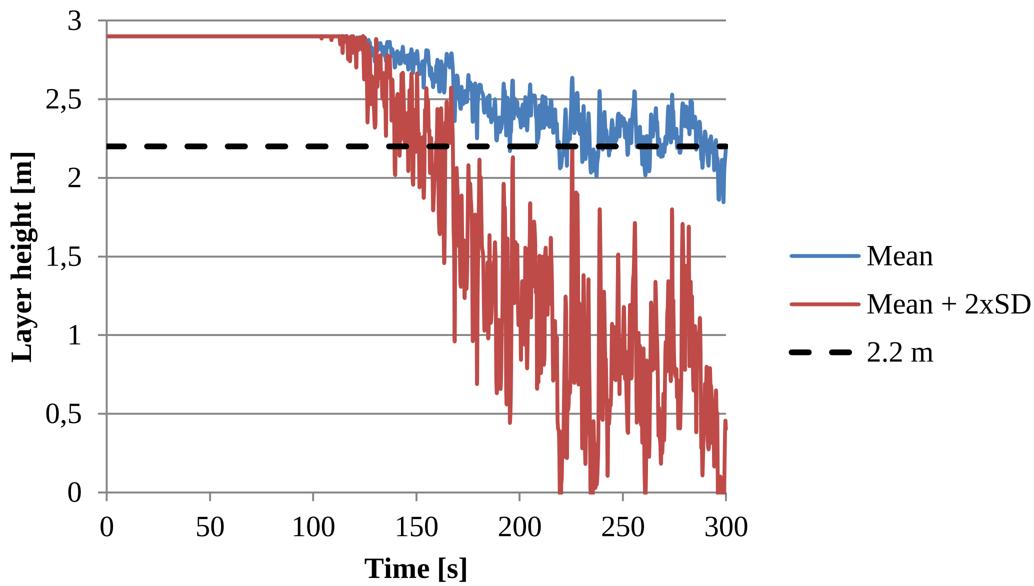


Figure 3-40: Layer height evolution in the staircase, when the ceiling height is 2.9 m. The FDS outcomes are spatially distributed, so the mean layer height and the mean layer height plus two standard deviations are specified.

3.8.3 ASET/RSET Analysis for Basement Floors (B1-B2)

3.8.3.1 CFAST Model

One of the car park levels was modeled in CFAST. The openings between the parking area and the staircase are all open, meaning that the smoke will move from the parking area through the small safety compartment located before the staircase, before ending up in the staircase itself. Therefore three different ASETs must be determined:

- An ASET for the parking area;
- An ASET for the safety compartment between the parking area and the staircase;
- An ASET for the staircase.

The vehicle ramp has been modeled as a large opening to the outside. The design fire is located centrally in the parking space.

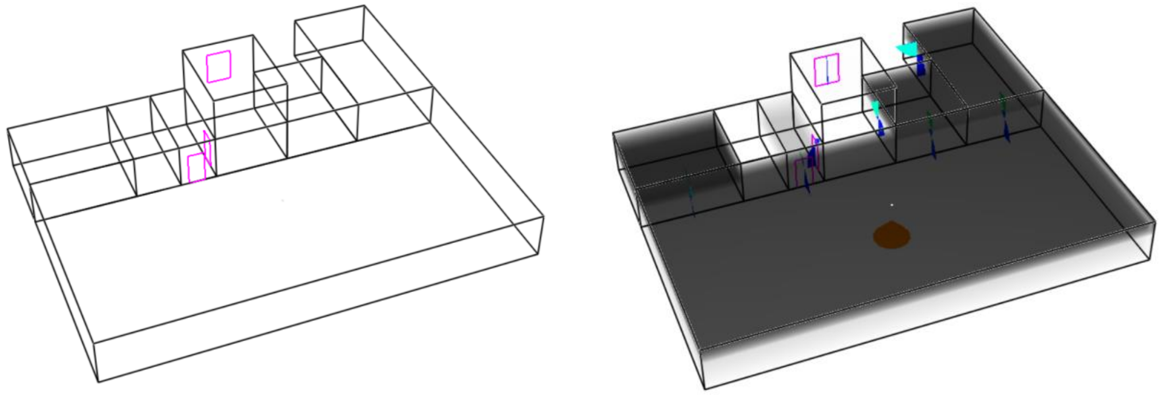


Figure 3-41: CFAST model of one basement level. The vehicle ramp is modeled as an opening. All doors between the parking area and the staircase are assumed open.

3.8.3.1.1 Design Fire Inputs

As described in section 3.5.1, the design fire shall have:

- A slow fire growth rate $\left(\alpha = 0.00358\ \frac{\text{kW}}{\text{s}^2}\right)$.
- A peak HRR of 9854 kW.

As the main goal of this performance based design is life safety of the occupants, the decay phase of the HRR evolution is not considered to be of importance when evaluating the performance criteria. The HRR plot is shown on Figure 3-42.

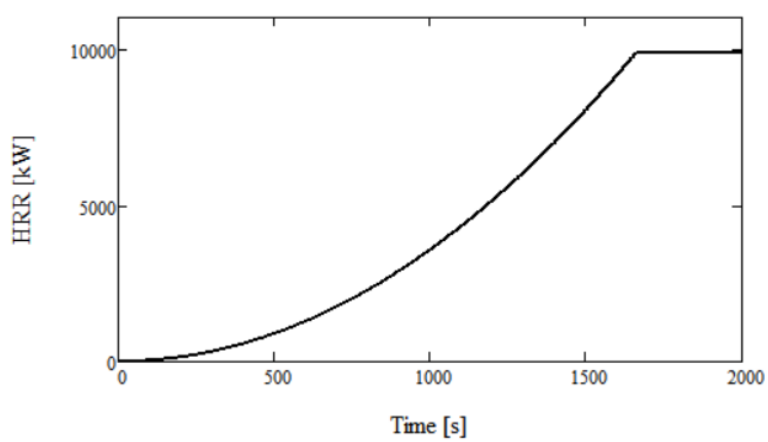


Figure 3-42: HRR evolution for a vehicle design fire.

A vehicle consists mainly of the polymers polypropylene, polyurethane and nylon. Their respective heat of combustion values range from 24.7 MJ/kg to 44.0 MJ/kg [33]. The three polymers have all been tested in CFAST, and it was determined that nylon produced the most severe conditions in the model. The relevant properties for nylon are listed in Table 3-17 below.

Material	**Nylon**
Chemical formula	$C_{25}H_{42}N_2O_6$
Heat of combustion [MJ/kg]	24.7
Soot yield [g/g]	0.03
CO yield [g/g]	0.08

Table 3-17: Properties for the fuel used in the vehicle design fire.

The maximum fire area (see Figure 3-43) was chosen to fit the floor area that a car fills out. The maximum fire area is 6 m^2, which will be reached more quickly than the peak HRR. The fire is located 0.5 m above the floor.

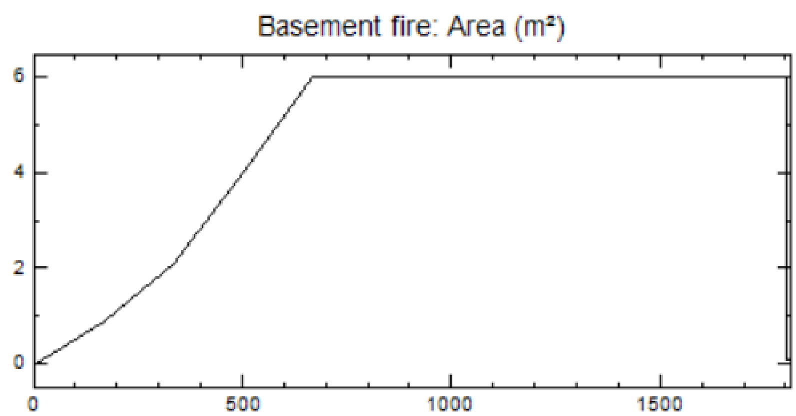


Figure 3-43: Evolution of fire area for the vehicle design fire. The peak area is 6 m^2 and is reached faster than the peak HRR.

3.8.3.2 Detection & Pre-movement Time

The automatic detection time is calculated in CFAST to 22 s.

Because the basement is connected to the office floors, the same pre-movement times as assumed for the office floors in section 0 will be applied. However, only the 60 s during which 90% of occupants will initiate evacuation will be used in the RSET analysis, resulting in a constant pre-movement time.

3.8.3.3 Evacuation Time

The entire basement compartment has been built in Pathfinder with 28 occupants on each level. This way, the effect of the queuing time in the staircase is accounted for, as the fire strategy for the building posits that both floors evacuate.

The evacuation time is found by human movement simulations in Pathfinder. All rooms on the ground floor have been modeled along with exits and occupants. The average walking velocity is set to 1.17 m/s with a standard deviation of 0.22 m/s as defined in section 3.2. Evacuation times based on the mean velocity and the mean velocity +/- 2 standard deviations will be examined.

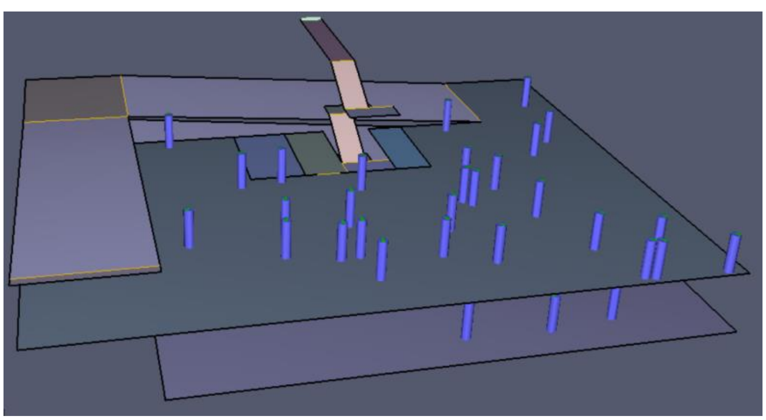


Figure 3-44: Screenshot of Pathfinder Basement Model.

Figure 3-45 shows the evacuation time as a function of the exit width, both for doors and stairways.

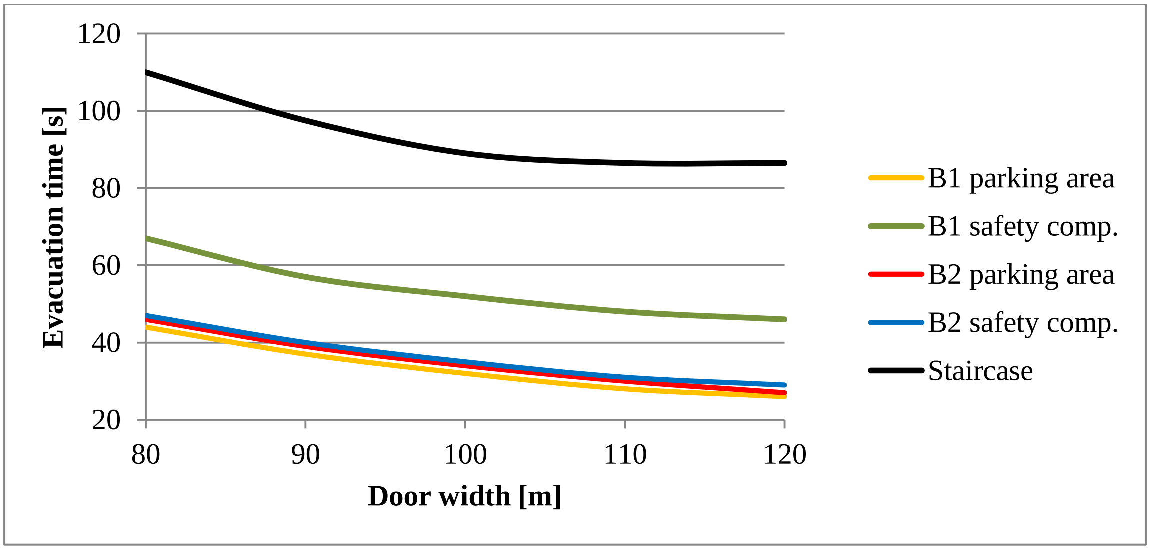


Figure 3-45: Evacuation times as dependent on exit widths. The safety compartment is the compartment between the parking area and the staircase.

Based on the data visualized on Figure 3-45, door and stairway widths of 1.10 m will be maintained. The evacuation process has been evaluated with varying velocities. The velocities shown in Table 3-18 are equal to the average velocity, and the average velocity +/- two standard deviations for exit widths equal to 1.10 m. The evacuation times in Table 3-18 does not include pre-movement times.

Velocity [m/s]	**0.73**	**1.17**	**1.61**
Evacuation time [sec] Parking area	34	30	29
Evacuation time [sec] Safety compartment	58	48	40
Evacuation time [sec] Staircase	135	87	74

Table 3-18: Evacuation time based on the mean velocity and the velocities two standard deviations away.

3.8.3.4 Evaluation of Trial Designs

The results from section 0 and 3.8.2.4 for the upper and lower velocity values will be combined to the total RSETs for the small store.

Fire scenario	Trial design	Detection + Notification time	Pre-movement time	Evacuation time	RSET	ASET	ASET > RSET?
Parking area	Automatic detection system, no sprinklers	22	60	34	116	150	YES
	Automatic detection, sprinklers					150	YES
Safety comp.	Automatic detection system, no sprinklers	22	60	58	140	210	YES
	Automatic detection, sprinklers					210	YES
Staircase	Automatic detection system, no sprinklers	22	60	135	217	345	YES
	Automatic detection, sprinklers					345	YES

Table 3-19: RSETs and ASETs when the lower velocity fractile is used.

Fire scenario	Trial design	Detection + Notification time	Pre-movement time	Evacuation time	RSET	ASET	ASET > RSET?
Parking area	Automatic detection system, no sprinklers	22	60	29	111	150	YES
	Automatic detection, sprinklers					150	YES
Safety comp.	Automatic detection system, no sprinklers	22	60	40	122	210	YES
	Automatic detection, sprinklers					210	YES
Staircase	Automatic detection system, no sprinklers	22	60	74	156	345	YES
	Automatic detection, sprinklers					345	YES

Table 3-20: RSETs and ASETs when the upper velocity fractile is used.

The first evaluation of the trial designs shows that the design of the basement is adequate when the floor-to-ceiling height is 2.75 m. It also showed than a fire suppression system in the form of sprinklers does not affect the ASET as the sprinklers do not actuate before after 262 sec.

3.8.3.5 Evaluation of Performance Criteria

Figure 3-46 shows the time evolution of the temperature and smoke layer height in the basement. As the plots show, the temperature criteria are far from the benchmarks, while the layer height falls rapidly below its tenability limit. Consequently, the layer height criteria will need to be examined further.

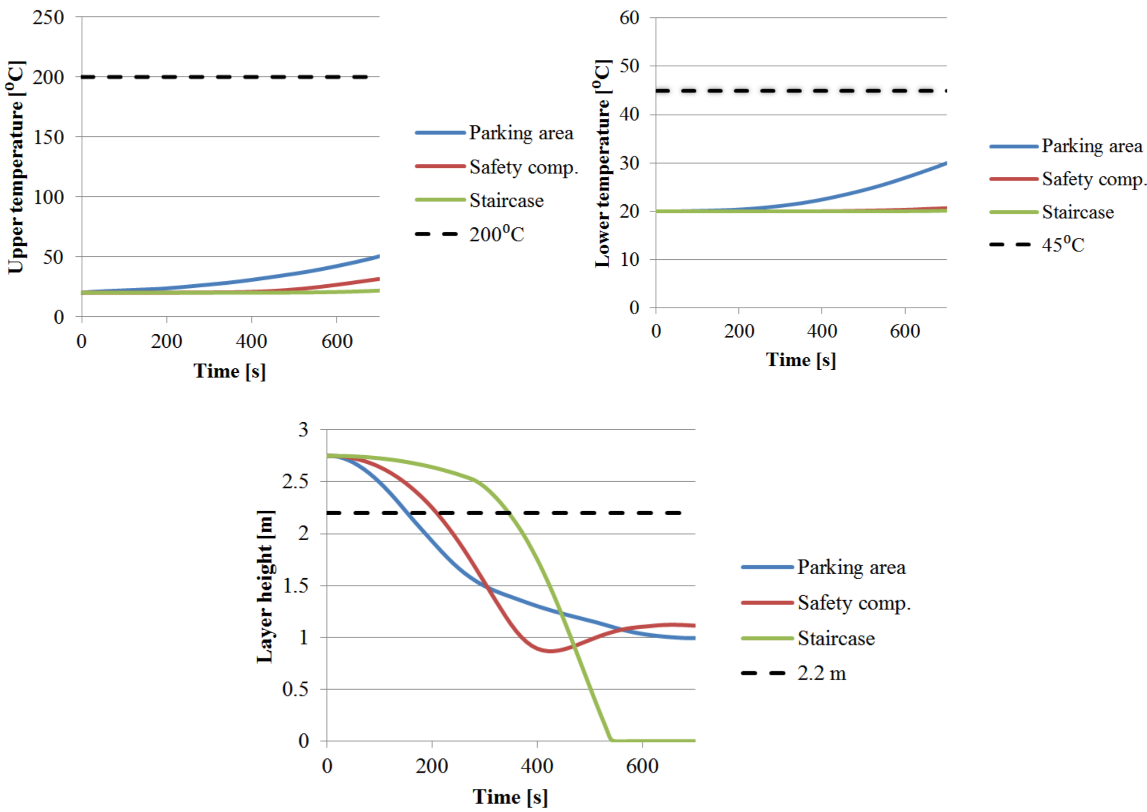


Figure 3-46: Time evolutions of smoke layer height and temperatures. The dashed lines indicate performance criteria limits.

3.8.3.6 Re-evaluating Trial Designs

In order to verify the robustness of the basement, the design was exposed to a fire with a fire growth rate twice as high as the initial one (from 0.00358 kW/s^2 to 0.00716 kW/s^2). The outcome is two different ASETs which will be held against the RSETs depending on the velocity of the occupants.

The plots in Figure 3-47 indicate that the design of the basement allows for occupants to evacuate in adequate time, while still providing an extra safety buffer before the layer height performance criterion is exceeded. This is the case for both the expected severe design fire and for the design fire with a doubled fire growth rate.

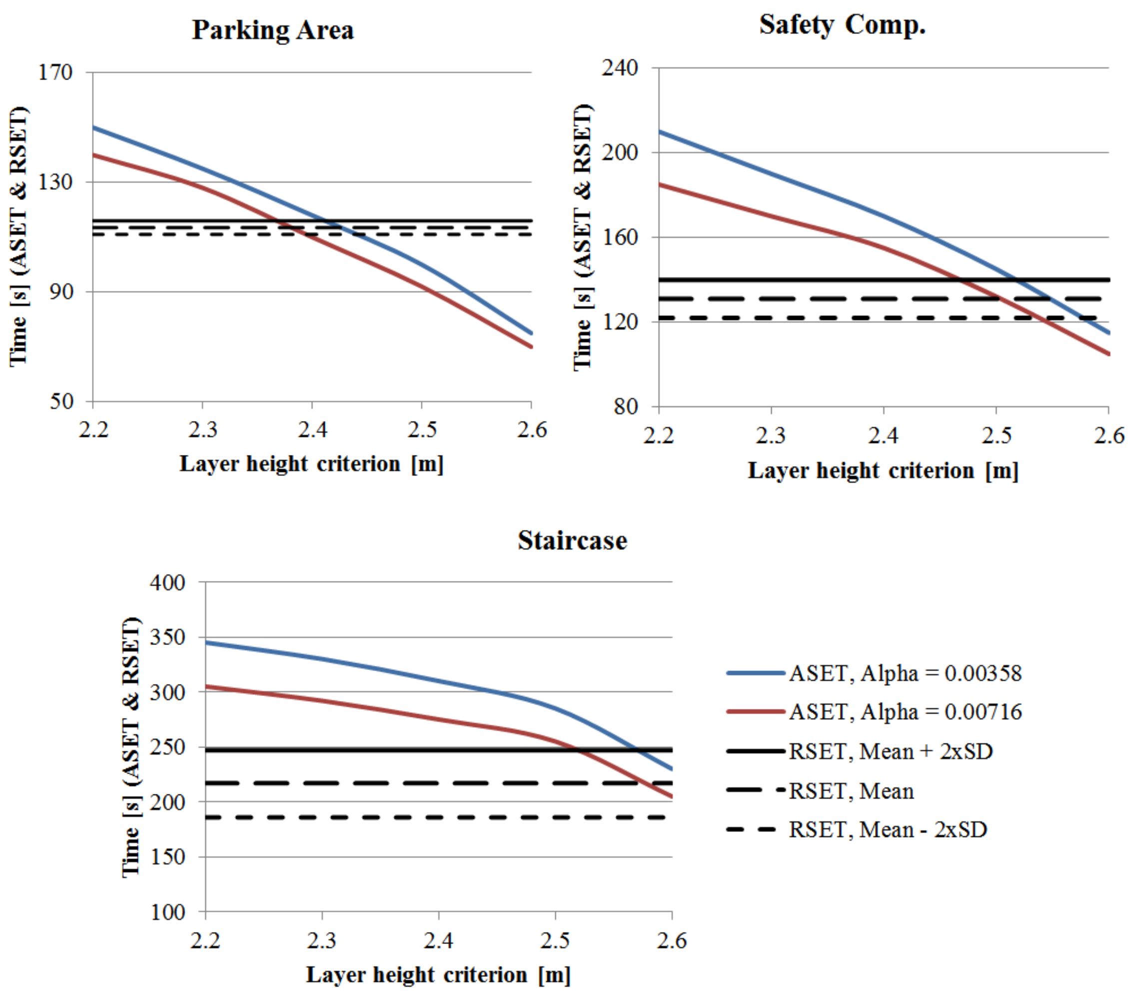


Figure 3-47: RSETs vs. ASETs for the different areas on in the basement. The RSETs (Black lines) are based on various occupant velocities, while the ASETs (Colored lines) depend on fire growth rate. Alpha = Fire growth rate. SD = Standard deviation.

3.8.4 Structural Integrity

The performance criteria for the structural integrity of the building is that it must be preserved in the basement, ground floor and 1st floor for at least 380 minutes and 170 minutes for the remaining upper floors. These numbers are based on the time it takes for the fire to burn out, which is calculated using a time equivalence formula. The calculations are conducted in Appendix A.

Fire resistance ratings typically range from 30 min. to 4 hours. The 380 min are equal to more than 6 hours, which is thus outside the spectrum of fire resistance ratings. Instead, the maximum value available is chosen. Subsequently a fire resistance rating of 4 hours (240 min.) for the basement levels, the ground floor and the 1st floor is required. For the remaining upper floors L2-L7, the fire resistance rating provided must be 3 hours (180 min.).

3.9 Final Design

A Performance-Based Design process has been executed for the high-rise office building, resulting in a final design of the building. Firstly, the building and occupant characteristics were described before the goals, objectives and performance criteria for the building were established. The only goal for this PBD was life safety, which the building has thus been designed for. The most severe design fires for the different occupancies in the building were identified, followed by an evaluation of trial designs for each type of occupancy: The car park basement, the retail ground floor and the upper office floors.

The PBD execution was an iterative process. After the first round of trial designs, the performance criteria were then re-visited and reevaluated in order to ensure the robustness of the design. If the trial design passed the initial performance criteria, but failed the reevaluated ones, then the trial designs also had to be rethought before being assessed by the new performance criteria. The initial trial designs involved egress provisions, adjustments of clear exit widths and implementation of fire safety features such as automatic detection and fire suppression, while the second trial designs could also include enhancement of ceiling heights and reductions of pre-travel activity.

For the basement floors, one solution was developed, while two different solutions were generated for the ground and upper floors.

3.9.1 Basement Levels (B1-B2)

The final design of the basement levels consists of:

- One exit leading to one exit staircase as visualized on Figure 3-48. Both exit doors have a clear width of 1.10 m, which is equal to an actual door width of 1.40 m.
- The stairways have a clear width of 1.10 m.
- A fire compartment between the parking area and the staircase is required.

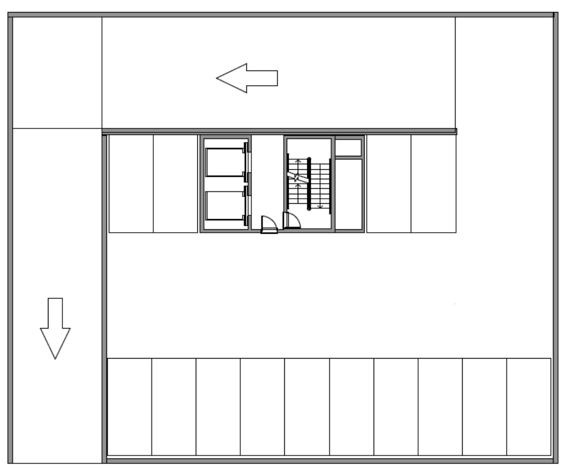


Figure 3-48: Floor plan of basement.

- Exit signs must be placed at a height of maximum 2.20 m.
- Automatic detection system with 0 sec notification delay is required.
- Structures must have a fire resistance rating of least 4 hours.
- No fire suppression or smoke control systems are required.
- A minimum floor-to-ceiling height of 2.75 m is required.

This final design of the basements yields the following safety factors for a mean walking velocity and the 90% fractile of the pre-movement time:

	RSET [s]	ASET [s]	Safety factor
Parking area	113.5	150	1.32
Safety Comp.	131	210	1.60
Staircase	217	345	1.40

Table 3-21: Safety factors of the basement floor.

3.9.2 Ground Floor

The final design of the ground floor consists of:

- Exits as visualized on Figure 3-49. Doors heights are 2.00 m.
- All walls that are visible on the floor plan on Figure 3-49 must be compartment walls.

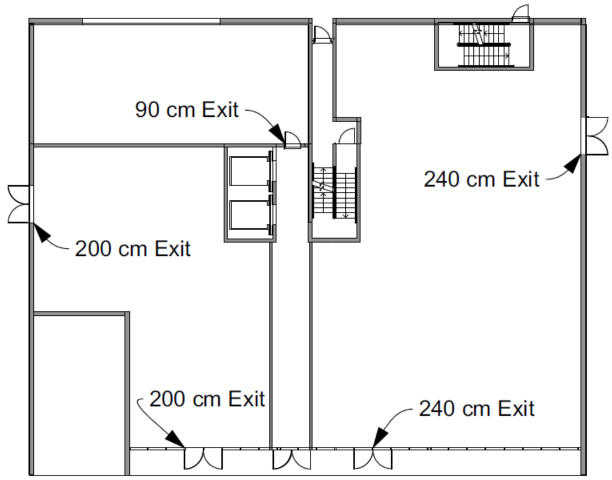


Figure 3-49: Floor plan of ground floor. Exit widths are shown.

- Exit signs must be placed at a height of maximum 2.20 m.
- Automatic detection system with 0 sec notification delay is required.
- Structures must have a fire resistance rating of at least 4 hours.
- No fire suppression system is required.
- Stairwell pressurization shall be provided.

- One of the following options are required:
  - Increasing the ceiling height from 3.0 m to 3.5 m.
  - Provide the retail staff with fire safety training that will enable them to instruct occupants to evacuate immediately upon notification.

This final design of the ground floor yields the following safety factors in Figure 3-21 for a mean walking velocity and the 95% fractile of the pre-movement time:

	RSET [s]	ASET [s]	Safety factor
Small store	66	104	1.58
Large store	92	134	1.46
Storage room	47	87	1.85

Table 3-22: Safety factors of the ground floor.

3.9.3 Upper floors (L1-L7)

The final design of the upper floors (L1-L7) consists of:

- Exits as visualized on Figure 3-50, with clear widths of doors and stairways equal to 1.60 m (Actual widths = 1.90 m). Doors heights are all 2.0 m.
- No partial compartmentation on any floor, except for the elevator and staircase shafts.

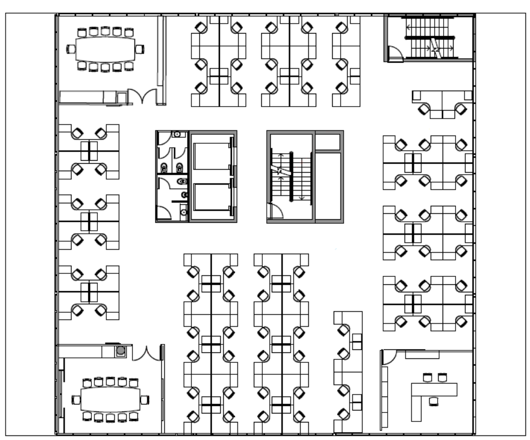


Figure 3-50: Floor plan of regular office area.

- Exit signs must be placed at a height of maximum 2.20 m.

- Automatic detection system with 0 sec notification delay is required.
- Structures must have a fire resistance rating of at least 4 hours on the 1st floor, and 3 hours on the remaining upper floors.
- No fire suppression system is required.
- Stairwell pressurization shall be provided. The smoke control system must be sized based on 4 open doors.
- One of the following options are required:
    - Increasing the ceiling height from 2.7 m to 3.1 m.
    - Increasing the ceiling height from 2.7 m to 2.9 m, while providing appropriate staff with fire safety training that will enable them to instruct other occupants to evacuate immediately upon notification.

This final design of the upper floors yields the following safety factors for a normal distributed walking speed, and the 90% fractile of the pre-movement time:

	RSET [s]	**ASET [s]**	**Safety factor**
Office area	123	140	1.14

Table 3-23: Safety factors of office floors.

Chapter 4 Execution of Prescriptive Designs

The purpose of this chapter is the application of prescriptive codes to the building. Prescriptive codes from three different countries will act as the foundation for the applications, resulting in three diverse building designs that will serve as benchmarks for an adequate level of fire safety. Three benchmarks are examined as there is no universal adequate level of safety. The countries and respective main life safety codes in question are:

- Australia (AU): *The Building Code of Australia (BCA* [57]
- USA: *NFPA 101 Life Safety Code* [58]
- England (UK): *Approved Document B, Vol. 2, Buildings other than Dwellinghouses (ADB)* [60]

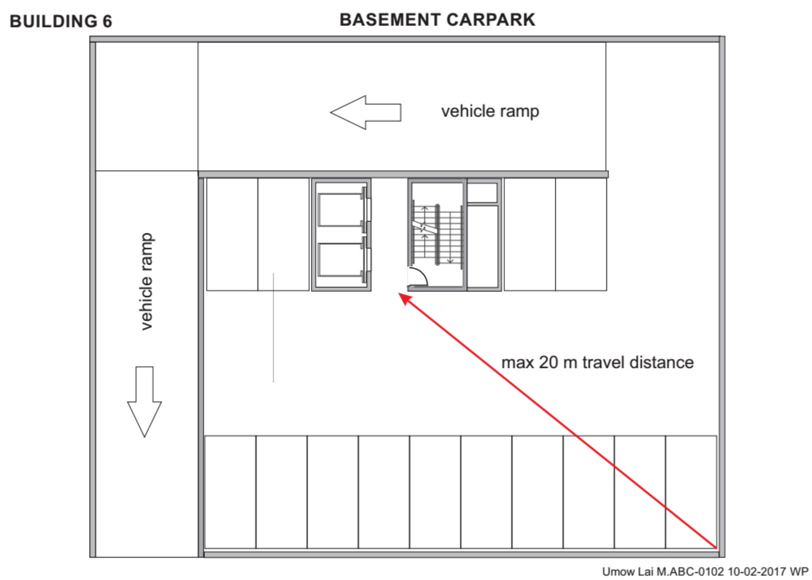
The various national codes are used in order to obtain a fuller picture of the methodologies utilized and provisions set by prescriptive codes. Examining three different codes rather than just one will enhance the comprehension of prescriptive methods and what an adequate level of fire safety is. The methods may include determination of minimum number of exits and clear widths, allowed maximum distance of travel, fire safety systems requirements, defining occupant densities etc.

Firstly, the three codes will be applied, starting with the Australian codes, followed by the American codes and terminating with the English codes. Afterwards, a brief comparison of the structures and methodologies of the codes will be conducted, followed by a comparison with the Performance-Based Design process and solution.

4.1 AU

4.1.1 Principal Building and Occupant Characteristics

4.1.1.1 Principal Building Characteristics

Building characteristics	
Occupancy	Class 7a – car park (B1 and B2) Class 6 – Retail (Ground) Class 5 – Office (L1 to L7)
Minimum construction type	Type A (not a large isolated building)
Floor plan	

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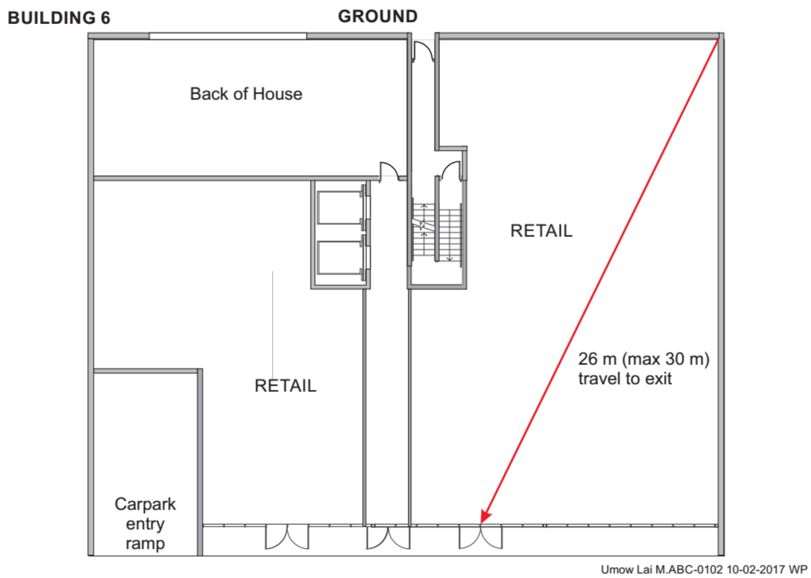
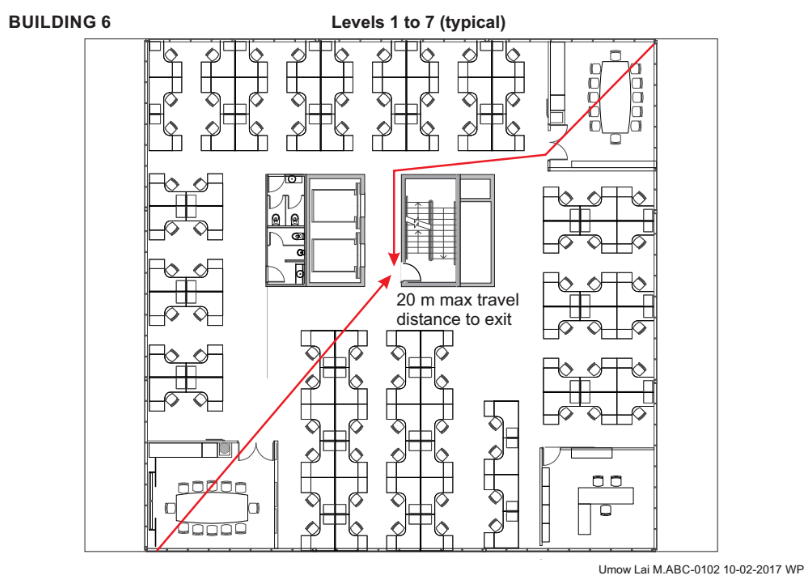




NB:
Level 1 also contains a library (half the floor area)
Levels 6 and 7 are interconnected by an internal open stairway.
</td>
</tr>
<tr>
<td>Height</td>
<td>Rise in Stories – 8
Effective Height – 24.9 m</td>
</tr>
</table>

	Floor-to-floor height • Basement – 3.0 m • Ground – 3.9 m • Levels 1 to 8 – 3.5 m Floor-to-ceiling height • Basement (floor to soffit) – 2.5 m • Ground – 3.0 m • Levels 1 to 8 – 2.7 m All doorways – 2.0 m
Width – Stairways, doors	Stairway width = 1.2 m Clear width of stairway (minus handrails) = 1.0 m Clear width of all doors = 750 mm
Construction materials	Car park level: • Concrete walls • Concrete floors Ground, Levels 1 to 8: • Reinforced concrete frame construction. • External walls – Double-glazed curtain wall construction • Internal walls –Timber studs at 600 mm centers lined with 10 mm standard plasterboard on each side • Floors and roof – 200 mm reinforced concrete slabs • Ceiling – Standard 10 mm plasterboard • Internal wall lining to common areas (corridors, stairway, lift lobby) – Pine
Openings in external walls	Curtail walls • Double glazed aluminum framed 6 safety glass • Located at 3 m distance away from side and rear boundary • Spandrel protection to all external openings with 900 mm upstand and 600 mm downstand.

	Shop front • Single glazed aluminum framed 10 mm safety glass
Location	Building located in a CBD area. Closest fire brigade station located 3 km away.

Table 4-1: Building characteristics.

4.1.1.2 Occupant characteristics

Characteristic	
Number and distribution	Basement (Car park): • 1 person per 30 m², (BCA Table D1.13) • 25 persons/floor Ground (Retail): • 1 person per 3 m², (BCA Table D1.13) • 169 persons/floor Levels 1 to 8 (Offices): • 1 person per 10 m², (BCA Table D1.13) • total 62 persons/floor
State	Assume aware and awake while they are in the building.
Level of assistance required	Mobility and disability is representative of the general population.
Emergency training	Assume that office and retail staff is trained in appropriate actions during an emergency, such that they are aware of exit locations and appropriate responses to alarm systems. It is appropriate to establish an Emergency Management Organization within the tenancy and provide staff training in accordance with AS3745 to facilitate evacuation.
Familiarity	Expect that occupants in the office areas to be familiar with the location of all exits and procedures to be taken during a fire event.

Table 4-2: Occupant characteristics.

4.1.2 Fire Safety System

4.1.2.1 Introduction

The building design is compliant with respect to the DtS fire safety provisions of Parts C, D and E of the BCA [57].

4.1.2.2 Fire Resisting Construction and Compartmentation

- The building has a rise in stories of 8 and is of Type A construction.
- The building structure is constructed of fire resistance walls, floors, columns and beams having the minimum Fire Resistance Levels (FRL) as required by the BCA. (Specification C1.1, provision 3.1, table 3).
    - *Car park (basement)*
        - Loadbearing elements 120/120/120
    - *Retail (Ground):*
        - Loadbearing elements 180/180/180
    - *Office (Levels 1 and 8):*
        - External walls
            - Loadbearing part 120/60/30
            - Non-loadbearing part -/-/-
        - External columns
            - Loadbearing 120/-/-
            - Non-loadbearing -/-/-
        - Floors, other internal loadbearing elements:
            - 120/120/120
        - Shaft wall
            - Loadbearing 120/90/90
            - Non-loadbearing -/90/90
        - Roof 120/60/30

- The openings (curtain walls) in the external walls the building are located 3 m from side or rear boundaries (section C3.2a).
- Spandrels or horizontal projections are constructed to separate the openings in the external walls and have an FRL of 60/60/60 (section C2.6a).
- All stair doors are self-closing fire-rated doors having an FRL of -/60/30 (section C3.4a, C3.8a).
- Penetrations through fire rated elements are protected in accordance with Specification C3.15 using an approved/tested system, e.g. penetrations for hydraulic service pipes, mechanical, ducts electrical conduits etc.
- Materials used in the building comply with Clause C1.10, C1.12 and/or Specification C1.10 as applicable.

4.1.2.3 Access and Egress

- Each ground level retail area has its separate exit that discharges directly to the outside (section D1.2b).
- The upper levels are served by one fire isolated stairway located centrally in the building (section D1.2b, D1.3b).
- The car park levels are served by two exits: the stairway and the vehicle ramp (gradient 1:8) (section D1.2c, D1.10c).
- The ascending and descending star flights are separated (section D2.4).
- The clear width of the stairway is 1.0 m (section D1.6).
- The maximum distance of travel in the office levels to the single exit is 20 m (section D1.4c).

- The maximum total travel distance to exit is 30 m for the retail area and 20 m in the car park level (section D1.4c).
- The maximum distance between alternative exits in the car park is less than 60 m (section D1.5c)
- The lift is not used for evacuation during fire emergencies.
- The open stairway connecting Levels 6 and 7 is not used for egress purposes.

4.1.2.4 Fire Services & Equipment

- Smoke detection and alarm system (Occupant Warning System) is installed throughout building (section E2.2, table E2.2a – buildings not more than 25 m in effective height).
- Heat detectors are installed in the car park level.
- A cause and effects matrix that summarizes the main alarm inputs and their effects on building services is provided in Table 4-3.

Alarm activation device	**Evacuation**	**Fire brigade call out**	**Lift homing**
Smoke or thermal detector	Sound alarm throughout building	No	No

Table 4-3: Occupant warning system, fire brigade call out and lift homing matrix.

- Fire hydrant coverage is provided in accordance with BCA Clause E1.3 and AS2419-2005.
- Fire extinguishers are provided throughout (section E1.6).
- Fire hose reels are provided throughout (4 m from stair door) (section E1.4).
- Exit signs must be installed above each door providing direct egress (section E4.5).

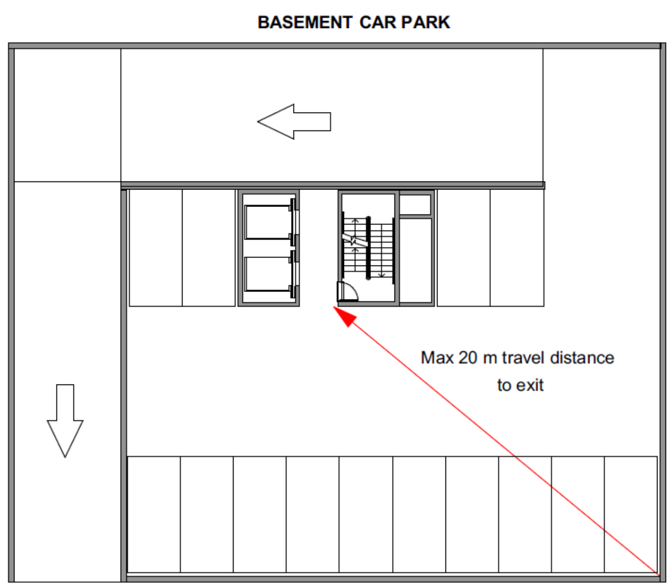
4.1.2.5 Maintenance and Management in Use

- Exits, fire hose reels and fire extinguisher cabinets are to be kept free from any storage or obstructions. This shall be checked every 6 months and records shall be kept on site.
- The staff will have a level of fire and evacuation training. Therefore, an Emergency Management Organization must be established in accordance with AS3745-2010.
- Management procedures will be implemented to ensure that the exits are available and that the exit paths are free (i.e. no object impeding/blocking egress). If locks are required at exits for patient safety, the locking mechanism will need to comply with clause D2.21 of the BCA. A mechanism is also to be provided that allows nursing staff to access bedrooms from outside when required.

4.2 USA

4.2.1 Principal Building and Occupant Characteristics

4.2.1.1 Principal Building Characteristics

Building characteristics	
Occupancy	Storage (NFPA 101 Chapter 42) – Car park (B1 & B2) Mercantile, subclass B (NFPA 101 Chapter 36) – Ground floor Business (NFPA 101 Chapter 38) – L1 to L7
Minimum construction type	New building High-rise building (NFPA 101 Chapter 11.8) Construction Type II (222) Separated occupancies
Floor plan	

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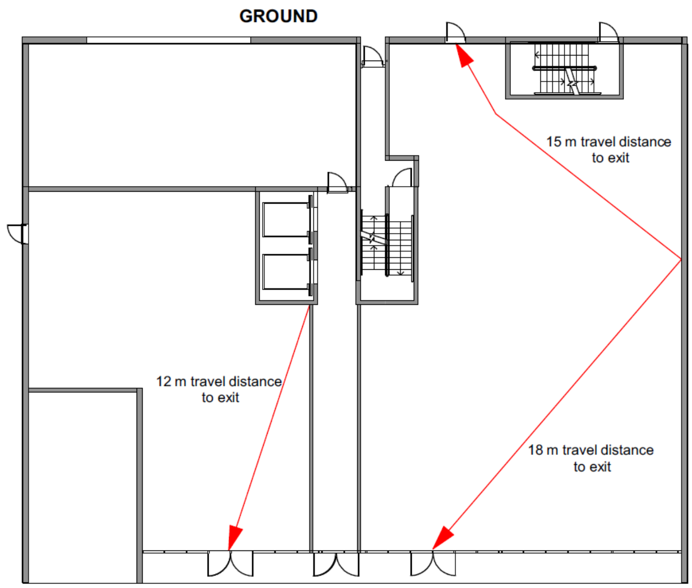
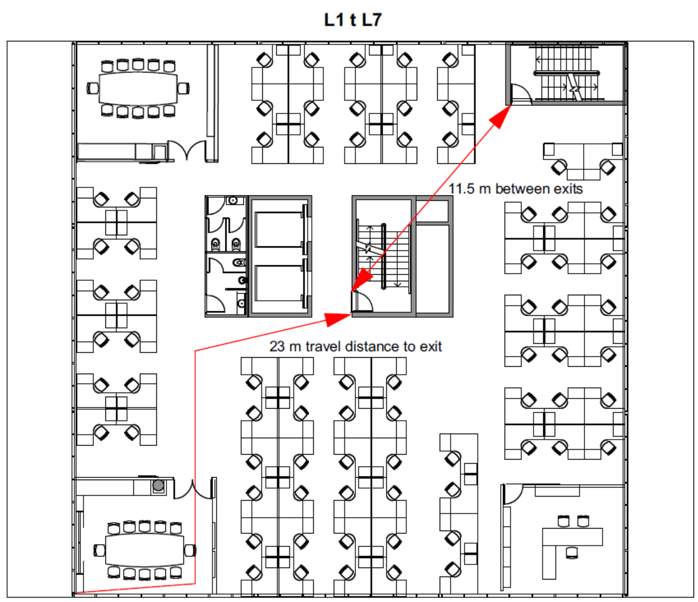




NB:
Level 1 also contains a library (half of the floor area)
Levels 6 and 7 are interconnected by an internal open stairway.
</td></tr>
<tr><td>Height</td><td>
Rise in stories - 8
Height to top floor - 24.9 m
Height of building – 28.4 m
</td></tr>
</table>

<table>
<tr><td></td><td>Floor-to-floor height:
B1 & B2 - 3.0 m
Ground - 3.9 m
L1 to L7 - 3.5 m
Floor-to-ceiling height:
B1 & B2 (floor to soffit) – 2.5 m
Ground – 3.0 m
L1 to L7 – 2.7 m
All doorways – 2.0 m</td></tr>
<tr><td>Width – Stair-ways, doors</td><td>Stairway width - 1.450 m
Clear width of stairway (minus handrails) – 1.250 m
Clear width of exit discharge doors in stairways – 970 mm
Clear width of remaining doors – 810 mm</td></tr>
<tr><td>Construction materials</td><td>The building is classified as ordinary hazard in accordance with section 6.2.
Car park level:
Concrete walls
Concrete floors
Ground & L1 to L8:
Reinforced concrete frame construction.
External walls – Double-glazed curtain wall construction
Internal walls – Timber studs at 600 mm centers lined with 10 mm standard plasterboard on each side
Floors and roof – 200 mm reinforced concrete slabs
Ceiling – Standard 10 mm plasterboard
Internal wall lining to common areas (corridors, stairway, lift, lobby) - Pine</td></tr>
<tr><td>Openings in ex-ternal walls</td><td>Curtain walls
Double glazed aluminum framed 6 safety glass
Shop front:
Single glazed aluminum framed 10 mm safety glass</td></tr>
</table>

Location	Building located in a CBD area. Closest fire brigade station located 3 km away.

Table 4-4: Building characteristics.

4.2.1.2 Occupant characteristics

Characteristic	
Number and distribution	Basement (Car park for offices): • 46.5 m^2/person (NFPA 101 table 7.3.1.2) • 17 persons/floor Ground (Mercantile, sales on street floor) • 2.8 m^2/person (NFPA 101 table 7.3.1.2) • 182 persons on ground floor L1 to L7 (Business use) • 9.3 m^2/person (NFPA 101 table 7.3.1.2) • 67 persons/floor
State	Assume that the occupants are aware and awake while they are in the building.
Level of assistance required	Mobility and disability of the occupants is representative of the general population.
Emergency training	We assume that employees and supervisory personnel in the mercantile and business areas are periodically trained in appropriate actions during an emergency and the use of portable extinguishers.
Familiarity	The occupants of the office areas are familiar with the location of all exits and procedures to be taken during a fire event.

Table 4-5: Occupant characteristics.

4.2.2 Fire Safety System

4.2.2.1 Introduction

The building design is compliant with respect to the NFPA 101 Life Safety Code provisions of chapters 4, 6, 7, 8, 9, 10, 11, 36, 38 and 42 [58] and NFPA 5000 Building Construction and Safety Code provisions of chapters 33 and 11 [20].

4.2.2.2 Fire Resisting Construction and Compartmentation

- The building is a high-rise structure with 8 stories and is of type II (222) construction (NFPA 5000 table 7.4.1) [20].
- All floors in the building are constructed as smoke barriers in accordance with section 8.5 (section 8.6.1).
- The building structure is constructed of fire resistant walls, floors, columns and beams having the minimum Fire Resistance Rating as required by NFPA 220 [59].
- Minimum fire resistance ratings for type II (222) from NFPA 220 table 4.1.1:
  - Exterior bearing walls: 2 hours
  - Interior bearing walls: 2 hours
  - Columns: 2 hours
  - Beams, girders, trusses and arches: 2 hours
  - Floor-ceiling assemblies: 2 hours
  - Roof-ceiling assemblies: 1 hours
  - Nonbearing walls: 0 hours
- All openings in fire rated elements (except in the smoke barrier separating the basement and the ground floor) are protected in accordance with section 8.3.4 and table 8.3.4.2 (section 8.3.4.1, 36.1.3.2.2, 38.1.3.2.2).

4.2.2.3 Access and Egress

- Each of the ground level mercantile areas are served by two exits as required by section 36.2.3.2
- The basement is served by one exit only. A single means of egress from the basement is permitted by section 42.2.4.1(2) as the exit can be reached within 30 m (table 42.2.5).
- The open stairway connecting L6 and L7 is not used for egress purposes.
- Two separate exits from each business floor as required by section 38.2.4.1(2).
- The maximum travel distance in the mercantile area is 250 ft (76 m) in accordance with section 36.2.6.2.
- The maximum travel distance in the business area is 300 ft (91 m) in accordance with section 38.2.6.3.
- The maximum travel distance in the car park is 200 ft (61 m) (42.8.2.6.1).
- The vehicle ramp in the basement serves as a means of egress as permitted by section 42.8.2.2.6.1(3).
- Two means of egress serve the basement as required by section 42.8.2.4.1.
- The minimum nominal width of the stairs including the handrails is 1120 mm in accordance with table 7.2.2.2.1.2(B), while it is 1450 mm due to the capacity of one staircase in accordance with section 7.3.3.2 is:

$$\frac{7 \text{ levels x } 67 \text{ persons/level}}{2} = 146.7 + \left(\frac{\text{Wn - 44}}{0.218}\right) \rightarrow \quad \text{Wn} = 144.2 \text{ in} = 1450 \text{ mm}$$

- All doors swing in the direction of egress travel as required by section 7.2.1.4.2.

- The minimum width of exit discharge doors in the stairways is 970 mm in accordance with section 7.2.1.2.3.2(9).
- The minimum width of the remaining doors is 810 mm as required by section 7.2.1.2.3.2.
- The minimum distance between two exits, exit accesses or exit discharges is 14 m on the ground floor and 11.5 m in the office areas in accordance with section 7.5.1.3.3.
- The lift is not used for evacuation during fire emergencies (section 9.4.1).

4.2.2.4 Fire Services & Equipment

- The building is protected throughout by an approved automatic sprinkler system in accordance with section 9.7.1.1(1). A sprinkler control valve and a waterflow device are provided for each floor (section 11.8.3.1).
- Both vertical exit stair enclosures are smokeproof enclosures in accordance with NFPA 5000 section 11.2.3, meaning that the staircases are pressurized (NFPA 5000 section 33.3.1).
- Both stair enclosures include fire doors tested under positive pressure in accordance with NFPA 252 (NFPA 5000 section 33.3.3.2).
- The building is protected throughout by a class I standpipe system in accordance with section 9.7 (section 11.8.3.2).
- A fire alarm system using an approved emergency voice/alarm communication system is installed in accordance with section 9.6 (section 11.8.4.1).
- A two-way telephone communication service is provided for fire department use in accordance with section 11.8.4.2.1 and 11.8.4.2.2.

- Emergency lighting in accordance with section 7.9 is provided (section 11.8.5.1).
- Marking of means of egress in accordance with section 7.10 is provided (section 36.2.10, 38.2.10, 42.8.2.10).
- Portable fire extinguishers are provided throughout the building in the mercantile and office areas (sections 36.3.5.3 & 38.3.5).
- Emergency actions plans complying with section 4.8 are provided in the building in the mercantile and office areas (sections 36.7.1 & 38.7.1).

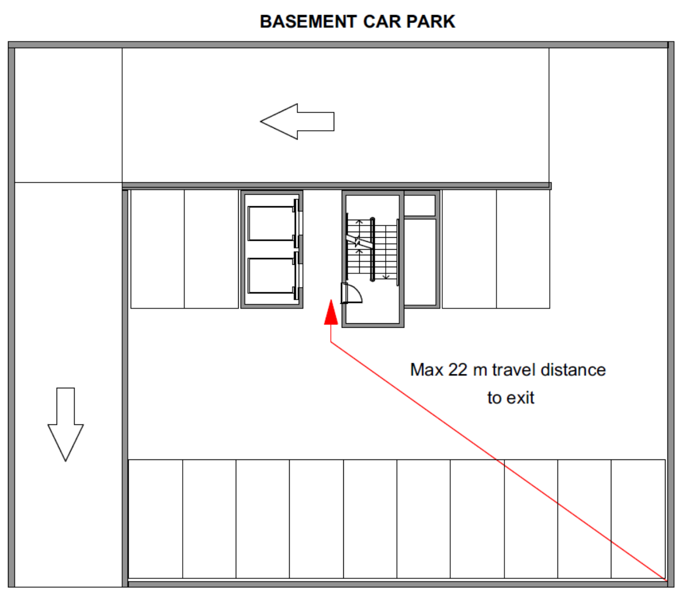
4.2.2.5 Maintenance and Management in Use

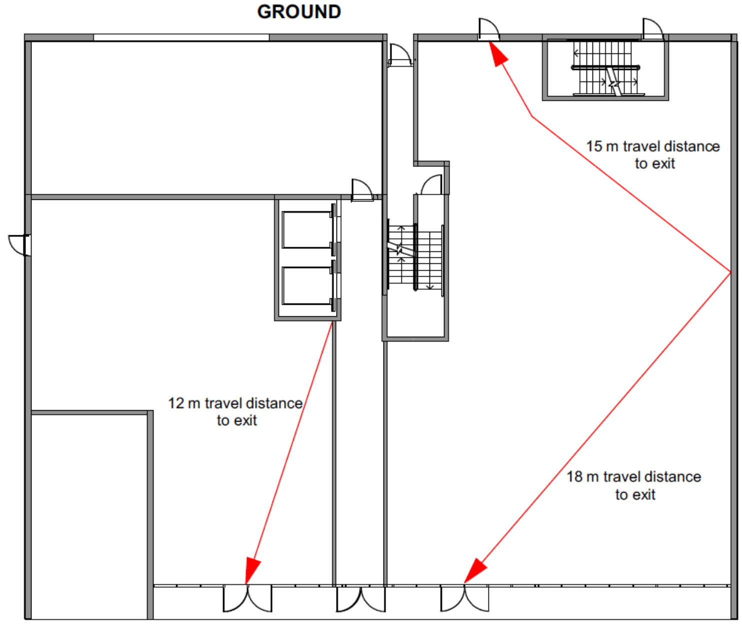
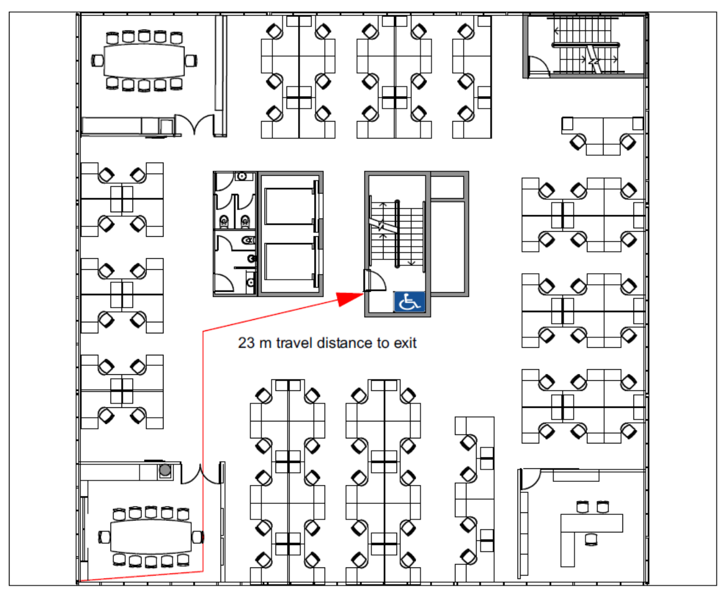
- Employees in the retail area shall be periodically trained in appropriate actions during an emergency in accordance with section 4.7 and instructed in the use of portable fire extinguishers (section 36.7.2).
- Employees and supervisory personnel in the business area shall be periodically trained in appropriate actions during an emergency in accordance with section 4.7 (section 38.7.3).
- Designated employees in the business area shall be periodically instructed in the use of portable fire extinguishers (section 38.7.2).
- When the fire alarm is initiated, it shall activate a general alarm in the building in order to notify the occupants and the fire department shall be notified (sections 38.3.4.3 & 38.3.4.4).

4.3 UK

4.3.1 Principal Building and Occupant Characteristics

4.3.1.1 Principal Building Characteristics

Building characteristics	
Occupancy	Group 7(b) – Car park (B1 & B2) Group 4 – Shop and commercial (Ground) Group 3 – Office (L1 & L2)
Minimum construction type	Refer to section 4.3.2.2. (Buildings other than dwellinghouses)
Floor plan	

	GROUND  **L1 t L7**  NB: Level 1 also contains a library (half of the floor area) Levels 6 and 7 are interconnected by an internal open stairway.
Height	Rise in stories - 8 Height to top floor - 24.9 m Height of building – 28.4 m

	Floor-to-floor height: • B1 & B2 - 3.0 m • Ground - 3.9 m • L1 to L7 - 3.5 m Floor-to-ceiling height: • B1 & B2 (floor to soffit) – 2.5 m • Ground – 3.0 m • L1 to L7 – 2.7 m All doorways – 2.0 m
Width – Stair-ways, doors	Stairway width - 1.2 m Clear width of stairway (minus handrails) – 1.0 m Clear width of discharge doors in stairways – 1850 mm Clear width of doors on B1, B2 and ground floor – 750 mm Clear width of doors on L1 to L7 – 850 mm
Construction materials	Car park level: • Concrete walls • Concrete floors Ground & L1 to L8: • Reinforced concrete frame construction. • External walls – Double-glazed curtain wall construction. • Internal walls – Timber studs at 600 mm centers lined with 10 mm standard plasterboard on each side. • Floors and roof – 200 mm reinforced concrete slabs. • Ceiling – Standard 10 mm plasterboard. • Internal wall lining to common areas (corridors, stairway, lift, lobby) – Pine.
Openings in ex-ternal walls	Curtain walls • Double glazed aluminum framed 6 safety glass Shop front: • Single glazed aluminum framed 10 mm safety glass

Location	Building located in a CBD area. Closest fire brigade station located 3 km away.

Table 4-6: Building characteristics.

4.3.1.2 Occupant characteristics

Characteristic	
Number and distribution	B1 to B2 (Car park, 14 parking spaces/level): • 2 persons/parking space (ADB table C1) • 28 persons/level Ground (Shop sales area): • 2 m^2/person (ADB table C1) • 254 persons on ground floor L1 (Half library/half office) • 7 m^2/person (Library, ADB table C1) • 6 m^2/person (Office, ADB table C1) • 97 persons/level L2 to L7 (Offices) • 6 m^2/person (ADB table C1) • 104 persons/level
State	Assume that occupants are aware and awake while they are in the building.
Level of assistance required	Mobility and disability of the occupants is representative of the general population.
Emergency training	The employers of the shops and the office areas are responsible for fire safety duties in accordance with The Regulatory Reform (Fire Safety) Order 2015. They are assumed to be trained in appropriate actions during an emergency. They are responsible for providing staff with fire safety management training and that fire safety systems are maintained.

Familiarity	Expect occupants of the office areas to be familiar with the location of all exits and procedures to be taken during a fire event.

Table 4-7: Occupant characteristics.

4.3.2 Fire Safety System

4.3.2.1 Introduction

The building design is compliant with respect to The Building Regulations 2010 fire safety provisions listed in the Approved Document B Volume 2 [60] and The Regulatory Reform (Fire Safety) Order 2005 of parts 1 and 2 (RRFS). [61]

4.3.2.2 Fire Resisting Construction and Compartmentation

- Both stairways and the lift are protected within a fire-resisting enclosure (compartment walls) (section 4.32 & 8.7).
- The floor above the basement and the floor above the ground floor are compartment floors (section 8.11).
- The walls surrounding the shopping areas are compartment walls (section 8.18).
- The compartment walls are extended up through the roof for a height of 375 mm above the top surface of the adjoining roof covering (section 8.31).
- All openings through fire separating elements are protected by sealing (openings for pipes) or fire dampers (openings for ducts) (section 10.2 & 10.9).
- All joints between fire-separating elements are fire-stopped (section 10.7)
- The building structure is constructed of fire resistant walls, floors, columns and beams having the minimum Fire Resistance Rating as required by Approved Document B (table A1 & A2).

- Minimum fire resistance requirements of elements:
    - Structural frame, beam or column & loadbearing walls,
        - Basement: R 90
        - Ground floor: R 90
        - L1-L8: R 90
    - Floors & compartment floors: REI 90/90/90
    - Compartment walls: REI 60/60/60
    - Protected shafts: REI 90/90/90
    - External walls: RE 90/90 & REI 15
    - Roofs: REI 30/30/30
    - Firefighting shafts: REI 120/120/120
    - Fire-resisting construction (wall between shop and storage room): REI 30/30/30
    - Cavity barriers: EI 30/30
    - Ceilings: EI 30/30
    - Ducts: EI 30/30
- All fire doors (the doors in the stairways) are fitted with a self-closing device (Appendix B, section 2).
- Minimum fire resistance of door in terms of integrity: FD 30S

4.3.2.3 Access and Egress

- Each of the ground level shops have two separate exits that discharge directly to the outside.
- The upper levels are served by two fire isolated stairways.
- The basement is served by one exit only.
- The minimum number of escape routes/exits in the car parking area based on number of occupants is 1 (Table 3).

- The minimum number of escape routes/exits in each of the two shops based on number of occupants is 1 (Table 3), but there has to be two exits due to the requirement of maximum travel distance (Table 2).
- The minimum number of escape routes/exits in the office area based on number of occupants is 2. (Table 3)
- The maximum travel distance in the shop area for more than one direction is 45 m in accordance with section 3.5.
- The maximum travel distance in the office area for more than one direction is 45 m in accordance with section 3.5.
- The maximum travel distance in the car parking area for one direction is 25 m in accordance with section 3.5.
- Escape routes in the same room are 45^0 or more apart in directions where it is possible (section 3.9).
- The minimum width of the escape routes and exits in each of the two shop areas is 750 mm (section 3.18, table 4)
- The minimum width of the escape routes and exits in the office areas is 850 mm (section 3.18, table 4)
- The minimum width of the escape routes and exits in the car parking area is 750 mm (section 3.18, 3.21, table 4)
- The minimum clear width of the corridor on the ground floor is 750 mm (section 3.18, table 4).
- The minimum clear width of the final exits in the stairways is 1803 mm. (section 3.18, table 4).

- Refuges are provided on each floor inside the central stairway in accordance with section 4.7. An area of 900 mm x 1400 mm is accessible to a wheelchair. The wheelchair space does not reduce the width of the escape route inside the stairway (section 4.9).
- The minimum clear width of both the stairways (between the handrails) is 1000 mm from the ground floor and up. The minimum clear width for the stairway leading from the basement to the ground floor is 1000 mm (section 4.15).
- All doors open in the direction of egress (section 5.14).
- The lifts are not used for evacuation during fire emergencies (section 5.39).
- The open stairway connecting L6 and L7 is not used for egress purposes.

4.3.2.4 Fire Services & Equipment

- The building is provided with an electrically operated fire warning system with manual call point sites adjacent to exit doors (section 1.29). The fire alarm system complies with BS 5839-1:2002 (section 1.30).
- The meeting rooms in the office areas are defined as inner rooms in accordance with section 3.10. Therefore all of the office area is fitted with an automatic fire detection and alarm system to warn the occupants in the meeting rooms of the outbreak of fire (section 3.10 iii).
- The basement and the storage area on the ground floor is provided with an automatic fire detection system (section 1.36).

- All refuges in the stairway on each floor is identified by a fire safety sign and a blue sign worded “Refuge – Keep clear” (section 4.10). An emergency voice communication system is provided at all refuges (section 4.11).
- The stairways are protected by a smoke control system designed in accordance with BS EN 12101-6:2005 (section 4.20 and 4.21).
- Both stairways and the car park are provided with escape lightning (section 5.36).
- All escape routes are marked by emergency exit signs (section 5.37).
- The basement is provided with a system of mechanical ventilation in accordance with section 11.6.
- The lift is designed as a firefighting shaft with a firefighting lift (section 17.2). The firefighting shaft is provided with fire mains with outlet connections and valves at every story (section 17.12).

4.3.2.5 Maintenance and Management in Use

- The responsible persons of the fire safety duties are the employers of the shops on the ground floor and the employers of the office area (RRFS section 3). The responsible persons in the building must co-operate with each other in order to comply with the requirements listed below (RRFS section 22).
- The responsible persons must:
    - Ensure that the building is equipped with firefighting equipment, fire detectors and alarms (RRFS section 13).
    - Ensure that escape routes and exits are kept clear at all times (RRFS section 14).

- Establish procedures such as safety drills to be followed in the event of serious danger to occupants (RRFS section 15).
- Ensure that any facilities, equipment and devices provided for fire safety are object to a suitable system of maintenance and are maintained in efficient state, in efficient working order and in good repair (RRFS section 17).
- Appoint one of more competent persons to assist her/him in undertaking the preventive and protective measures mentioned in this section (section 18).
- Provide her/his employees with comprehensible and relevant information on the risks to them, the preventive and protective measures and the procedures following an event of danger (RRFS section 19).
- Ensure that her/his employees are provided with adequate safety training (RRFS section 21).

4.4 Comparison

The application of the three prescriptive codes from Australia, USA and UK has resulted in three very different building designs, demonstrating that there is no universal benchmark for an adequate level of fire safety. The Verification Method can therefore not be benchmarked against a general prescriptive set of requirements, and will therefore primarily be assessed against one set of prescriptive codes, mainly the Australian. It is not only the outcomes of the three codes that vary from one another though, as the structures of the codes also differ considerably from each other.

The most comprehensive of the three codes is by far the American code, NFPA 101. NFPA 101 is very specific in its requirements, offering explicit limits and regulations. For instance, NFPA 101 outlines directions for any occupancy category imaginable in both existing and new editions, while Approved Document B (APB) only differs between dweillinghouses, flats and everything else. This comprehensiveness also means that NFPA 101 is the one of the three codes that expects the least of the engineer using it. Despite its general explicitness, NFPA 101's extensive lists of provisions can be puzzling to apply as well, as it can be difficult to assign prescriptive rules to complicated building structures.

While NFPA 101 is long and concrete, the British ADB is more flexible and short. E.g. when NFPA 101 requires that the building is fitted with a sprinkler system, ADB doesn't necessitate sprinkler systems, but instead offers lighter provisions if one should be installed. This flexibility demands a certain level of skills by the engineer, but unlike NFPA 101 and the Australian BCA, ADB provides examples and figures that are practical as guidance for the engineer.

The BCA is also short, but more explicit than ADB. The BCA commences with a long list of general performance requirements, before presenting the Deemed-to-Satisfy provisions. In addition to the DtS provisions, the BCA offers a verification method for avoiding fire spread as well, in case the DtS requirements cannot be met.

4.4.1 Comparison of Outcomes

A distinctive difference between the BCA design and the two others is the number of required exits. The BCA only requires one single exit for any area in the building, while NFPA 101 and ADB requires two exits for the all the ground floor areas and upper floors. However, determination of the number of exits is based on occupant load and maximum distance of travel for all three codes. ADB generally specifies the highest occupant loads, often notably higher than the other two codes, while the lowest distance of travel value is found in the BCA. Despite the inferior number of exits, the BCA also allows the narrowest door with. The BCA and ADB require the same stairway width, while NFPA entails a slightly wider stairway. All three codes agree that elevators should not be used for egress purposes.

The floor-to-ceiling heights in the building have been determined by either the designer or the stake holders, but codes in all three countries allow for lower heights, resulting in a more unsafe environment in the context of fire events. The height requirements are as follows:

- **USA**: 2.032 m (6'8'') for the car park and 2.134 m (7') for the remaining parts of the building. This is governed by The International Building and Residential Code [62].
- **UK:** 2.0 m in stairways and for egress routes and otherwise unlimited. This is governed by Approved Document K [63] and Approved Document B [60].
- **AU:** 2.0 m for stairways, 2.1 m for car parks, 2.4 m for the remaining parts of the building. This is governed by the BCA [57].

While Australia requires the highest floor-to-ceiling heights, they are still all below the heights chosen by the designer.

The UK design of the building has notably lower values for the fire resistance ratings than the AU and USA building designs, which generally agree about the fire resistance ratings for this particular building. Likewise, ADB only requires the floors between occupancy categories to act as compartments (the floor above and below the ground floor), while all floors that separate stories according to NFPA 101 must be smoke compartments. These points indicate that ADB generally provides the weakest structural requirements for fire safety.

The three codes have very dissimilar provisions regarding fire equipment of the buildings. NFPA prescribes sprinklers for the entire building as the only code to do so. Neither NFPA nor BCA suggest any smoke control systems, while ADB requests both a mechanical ventilation system in the basement and a smoke control system in the staircases. Meanwhile, ADB is the only code to not require automatic fire detection in the retail space. The UK and USA designs resulted in emergency lightning in the staircase and basement, while the AU and USA design provides portable fire extinguishers and standpipe systems. Despite these differences, all three codes agree that any staff in the building must receive appropriate fire safety training, but NFPA 101 is the only code to demand that the fire department is directly notified upon detection of fire.

4.4.2 Comparison to the Performance-based Design

The Performance-Based Design solution represents another benchmark for an adequate level of safety, although it differs fundamentally from the prescriptive design solutions. Some of the differences between the three prescriptive designs and the PDB are monumental. The dissimilarities are especially outspoken for the clear widths of the exit provisions, the required floor-to-ceiling heights and the fire resistance ratings. Generally, in order to comply with the performance criteria for the PBD, exit widths much greater than those appointed by the prescriptive codes are necessary. In addition to the wider exits, higher ceiling heights are needed, meaning that not only will the occupants take more time to get through the exit components; they will also have less time available before the space becomes untenable. The structure itself is also weaker for the prescriptive designs, as the fire resistance ratings are very low compared to those for the PBD. These fundamental differences indicate that the prescriptive codes fail to provide a sufficiently safe fire safety design of the building due to under design.

The undeniable advantages of the prescriptive codes are the fast application process and the lack of uncertainty of complying with the performance requirements. The Performance-based Design process requires a high level of skills of the fire safety engineer, which means that a PBD method can be undertaken by fewer persons than the prescriptive code method. Nonetheless, the reduced design time period and the accessibility of the prescriptive codes should not be chosen at the expense of an acceptable fire safety level.

Chapter 5 Execution of Verification Method

In this chapter, the Verification Method will be applied to the building. As a part of a calibration study by the Fire Protection Association Australia (FPA Australia) [64], the company Umow Lai has already applied the Verification Method to the building that was designed using the Australian prescriptive codes in order to verify the outcome. In this report, the design scenarios and assumptions for the building have already been proposed and analyses of the ASETs and RSETs for the design scenarios have already been carried out.

Firstly, a summary of the original FPA report will be provided for the purpose of the final critique of the Verification Method. An evaluation of the results of the report and the building design will follow the summary. If the application of the VM reveals that the building does not comply with the performance requirements, an alternate design of the relevant parts of the building will be proposed before an additional evaluation by applying the Verification Method will be conducted.

5.1 Summary of Report

In the FPA study, 26 design scenarios were developed. The author described modeling assumptions, methodologies and assumed sequences of events before computing the scenarios and comparing the results to the BCA designed building. In the following section, a summary of those assumptions and results will be provided.

The RSET and ASET manual calculations, equations, references, formulae and sample calculations are described in detail in Appendix D and Appendix E.

5.1.1 General Assumptions

The assumptions listed below for manual calculations and zone modeling are somewhat equal to those made by FPA in their report. However, some of the assumptions have been transformed slightly so that they match the assumptions made for the re-evaluation of the building design.

5.1.1.1 Manual Calculations (RSET)

No	Assumptions
1	Type A occupants.
2	In the office, storage and car park area, occupants are awake, alert and familiar with the building. In the retail area, occupants are awake, alert and unfamiliar with the building.
3	Mobility and disability is representative of the general population.
5	Occupancy: Car park (basement): 25 persons per level; retail (ground): 169 persons per level; office (L1-L7): 62 person per level.
6	Density: Car park (basement): 1 person per 30 m^2; retail (ground): 1 person per 3 m^2; office (L1-L7): 1 person per 10 m^2.
7	Estimated enclosure areas: Car park (basement): 500 m^2; retail (ground): 350 m^2; office (L1-L7): 575 m^2.
14	The maximum horizontal travel distance is determined from the building specifications and drawings.
16	The dimensions of stair riser and stair tread are equal to 178 mm and 279 mm, respectively (k = 1.08, S = 0.95 m/s).
17	The maximum vertical travel distance (L_{trav}) is determined as the sum of the distance to be travelled along the stairs. According to the building specifications and drawings, the flight length is assumed to be 3.10 m, the landing length 1.20 m. Occupants need to cover 2 flights and 2 landings in order to descend 1 level.
18	The lifts are not used for evacuation during fire emergencies. Only fire isolated

No	Assumptions
	stairways are used for egress purposes. The open stairway connecting the office level 6 and 7 is not used for egress purposes. The vehicle ramp in the car park is not used for egress purposes.
19	The evacuation time from the space is evaluated as the greater between the time taken to travel to an exit (horizontal travel) and the flow time

Table 5-1: Assumptions for manual RSET calculations.

5.1.1.2 Zone Modeling (ASET)

No	Assumptions
1	The geometry of buildings and compartments are modeled according to the building specifications and drawings.
2	Each compartment is modeled with adiabatic surfaces.
5	Smoke detection and alarm systems (occupant warning system) are installed throughout the building at a distance below the ceiling of 25 mm. Heat detectors are installed in the car park. • Heat detectors: *RTI* = 30 $m^{½}s^{½}$, T_{act} = 57°C, Radial distance = 4.2 m • Smoke detectors: Optical density at alarm = 0.14 m^{-1}, Radial distance = 7 m
6	Design fire characteristics: • Fast t-squared fire (α = 0.047 kW/s^2) up to flashover • Peak Heat Release Rate (HRR) = 20 MW • Soot Yield = 0.07 kg/kg (pre-flashover fire) • Heat of Combustion = 20 MJ/kg • Radiative Fraction = 0.35
7	Fire is modeled away from walls and corners.
8	The surface area of the fire is modeled as linearly increasing up to the peak heat release rate, from a minimum area (A_{min}) to a maximum area (A_{max}), defined according to the compartment dimensions (Example in Figure 5-1).
9	The base of the fire is located at 0.5 m from the floor level.
10	All fire and smoke doors fitted with self-closers are latched and closed.

No	Assumptions
11	No failure of self-closers of stairs doors, except in the fire scenarios RC1 – RC5.
12	No failure of automatic detection and occupant warning system, except in the fire scenarios RC6 – RC10.
13	No smoke leakage through the stairs doors and the staircase represents a safe egress route, except in the fire scenarios RC1 – RC5.
14	The staircases are modeled as independent compartments, connected through door openings.
15	As defined by NCC 2019 Fire Safety Verification Method Section 3.6, The ASET tenability parameters measured at a height of 2.0 m above floor level, are: a) An FED of thermal effects greater than 0.3. b) Conditions where, due to smoke obscuration, visibility is less than 10 m except in rooms of less than 100 m^2 where visibility may fall to 5 m.
16	The FED thermal tenability criteria is calculated as the time to experiencing pain due to convected heat accumulated per minute for fully clothed subjects.
17	The visibility tenability criterion is calculated assuming light-reflecting signs, which occurs at an aerosol mass concentration (C) of approximately 0.3 g/m^3L.

Table 5-2: Assumptions for zone modeling calculations for ASET.

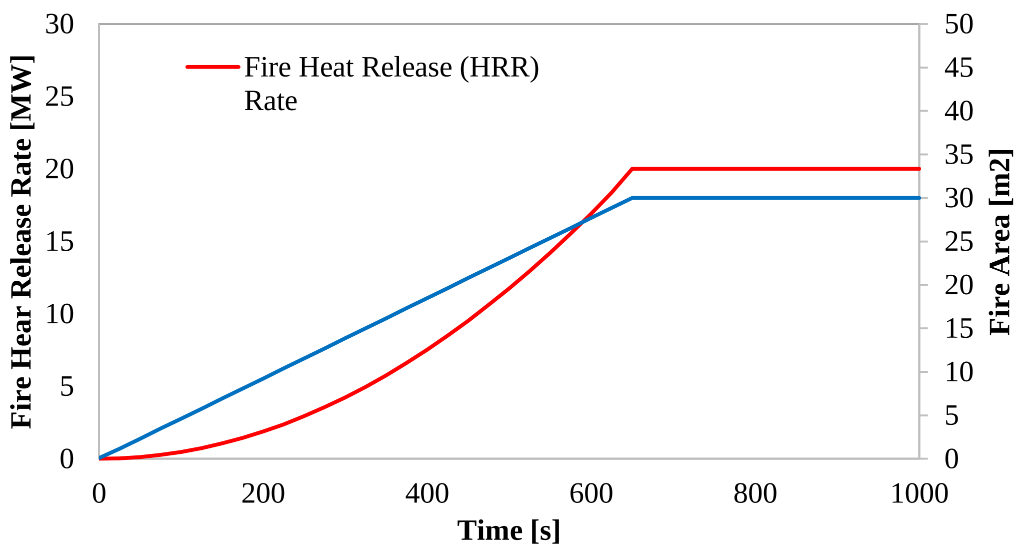


Figure 5-1: Example of fire heat release rate (HRR) and fire area growth implementation into CFAST (CF 2 fire scenario – Challenging fire in retail area)

5.1.2 BE1 – Fire blocks exit on a typical office floor level

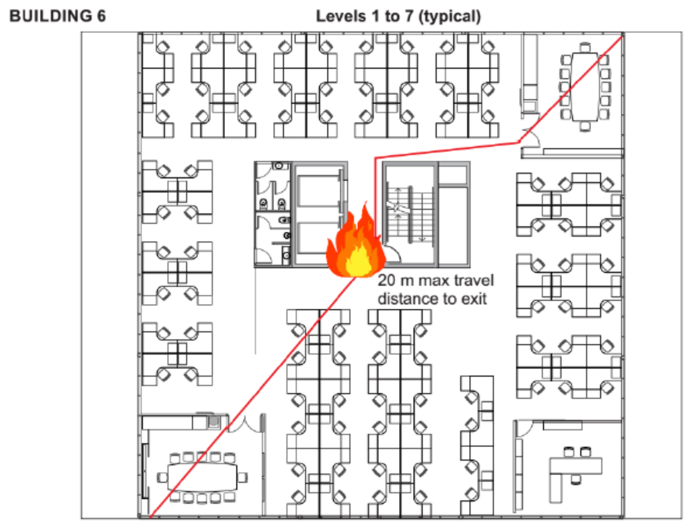


Figure 5-2: Location of design fire in the BE1 scenario.

This scenario hasn't been analyzed as there is only one exit and no occupants could evacuate the building. Therefore no ASET/RSET analysis has been carried out.

5.1.3 UT1 – Fire in a storage room in a typical office level

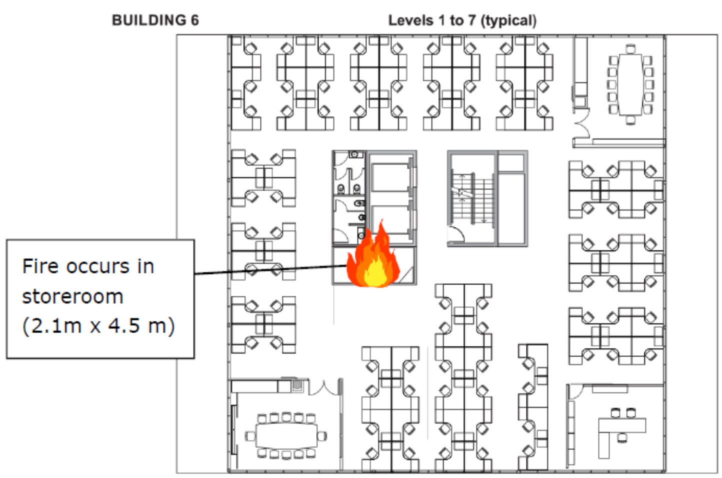


Figure 5-3: Location of design fire in the UT1 scenario. The fire occurs in a storage room.

Assumed sequence of events according to the FPA report:

No.	Event	Assumptions	Comments
1	Fire starts in a storage room at the center of a typical office floor (see Figure 5-3)	Building fully occupied. Fire starts in storage room (2.1 m x 4.5 m) and the base of the fire is 0.5 m above floor level. Fire grows at fast t^2 rate. Storeroom fire load density = 1800 MJ/m2	A sensitivity analysis may be required to determine whether a fire occurring within a lower level is worst or better than one occurring at a higher level.
2	Smoke detector activates and warning sounds throughout the building.	Smoke detector in the storage room is 25 mm below the ceiling and will activate at 0.14/m optical density.	Detection time determined via fire modeling.
3	Smoke spreads to office area through open door.	Storage room door fully open (no self-closer).	Rate and quantity of smoke spread is determined via fire modeling.
4	All occupants in the building prepare to evacuate	60 sec pre-movement activity time.	
5	All occupants commence movement at the same time and move into stairway or out of the building.	Travel speeds and flow rates as assumed in evacuation modeling.	Evacuation times determined via evacuation analysis.
6	Evacuation paths in building affected by the fire.	Conditions of the egress oaths monitored at various locations along the egress path.	Conditions are determined via fire modeling and checked against tenability criteria.
7	Stairway doors on all floor open while occupants move or queue at stairway entries.	Stairway doors open during evacuation	Queuing time determined via evacuation analysis.

No.	Event	Assumptions	Comments
8	Smoke spread into stairway and other parts of building via open stairway doors	Travel speeds and flow rates as assumed in evacuation modeling.	
9	Evacuation paths in building affected by the fire.	Conditions of the egress paths monitored at various locations along the egress paths.	Conditions are determined via fire modeling and checked against tenability criteria.

Table 5-3: Assumed sequence of events according to the FPA report.

5.1.4 UT2 - Fire in a storage room in a retail area

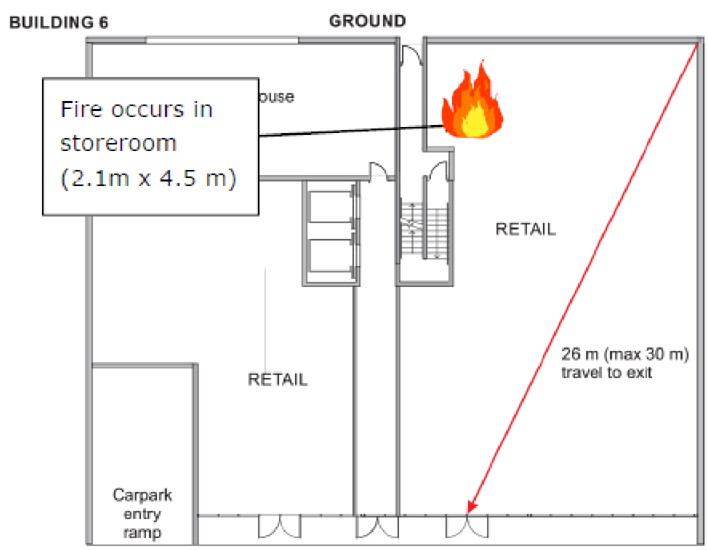


Figure 5-4: Location of design fire in the UT2 scenario. The fire occurs in a storage room.

Assumed sequence of events according to the FPA report:

No.	Event	Assumptions	Comments
1	Fire starts in a storage room at the back of a retail area on the ground floor (see Figure 5-4)	Building fully occupied. Fire starts in storage room (3 m x 3 m) and the base of the fire is 0.5 m above floor level. Fire grows at fast t^2 rate.	

No.	Event	Assumptions	Comments
2	Smoke detector activates and warning sounds throughout the building.	Smoke detector in the storage room is 25 mm below the ceiling and will activate at 0.14/m optical density.	Detection time determined via fire modeling.
3	Smoke spreads to retail area through open door.	Storage room door fully open (no self-closer).	Rate and quantity of smoke spread is determined via fire modeling.
4	All occupants in the building prepare to evacuate	60 sec pre-movement activity time.	
5	All occupants commence movement at the same time and move into stairway or out of the building.	Travel speeds and flow rates as assumed in evacuation modeling.	Evacuation times determined via evacuation analysis.
6	Evacuation paths in building affected by the fire.	Conditions of the egress oaths monitored at various locations along the egress path.	Conditions are determined via fire modeling and checked against tenability criteria.

Table 5-4: Assumed sequence of events according to the FPA report.

5.1.5 CS1 – Fire in ceiling space

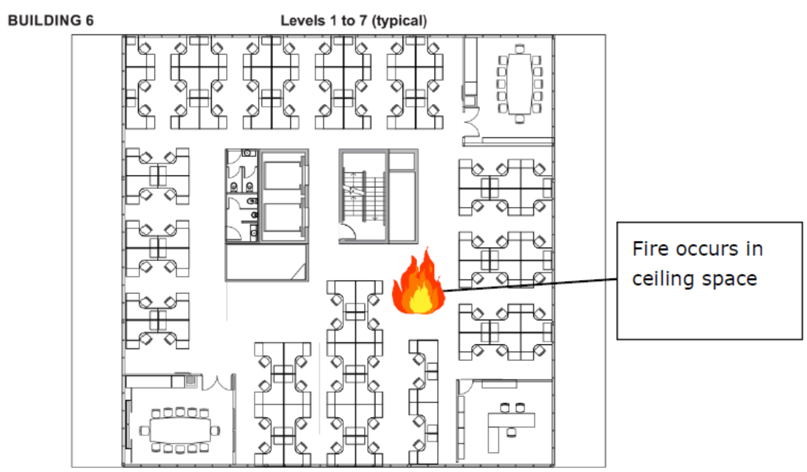


Figure 5-5: Location of design fire in the CS1 scenario. The fire occurs in the ceiling space.

Assumed sequence of events according to the FPA report:

No.	Event	Assumptions	Comments
1	Fire starts in a ceiling space within a typical office floor (see Figure 5-5)	Building fully occupied. Fire grows at fast t^2 rate.	
2	Smoke detector activates and warning sounds throughout the building.	Smoke detector within ceiling activates at 0.14/m optical density.	Detection time determined via fire modeling.
3	Occupants in the building prepare to evacuate.	60 sec pre-movement activity time.	
4	All occupants commence movement at the same time and move into stairway or out of the building.	Travel speeds and flow rates as assumed in evacuation modeling.	Evacuation times determined via evacuation analysis.
5	Evacuation paths in the building affected by the fire.	Conditions of the egress paths monitored at various locations along the egress path.	Conditions are determined via fire modeling and checked against tenability criteria.

Table 5-5: Assumed sequence of events according to the FPA report.

5.1.6 CF1 – Challenging Fire in Car Park

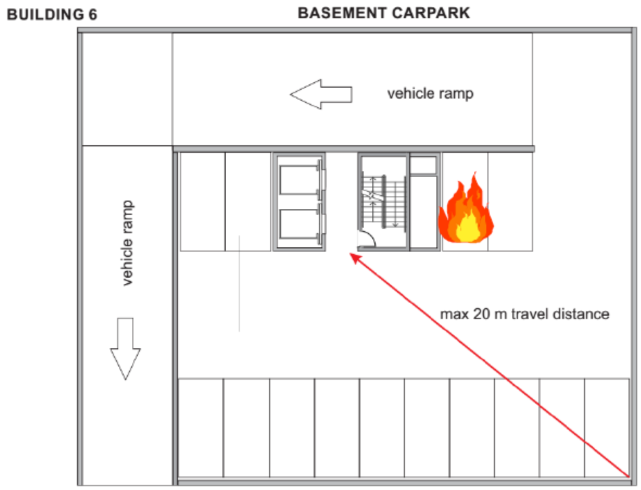


Figure 5-6: Location of design fire in the CF1 scenario in the basement.

Assumed sequence of events according to the FPA report:

No.	Event	Assumptions	Comments
1	Fire starts in a car near the stairway on the B2-level (see Figure 5-6).	Building fully occupied. Fire starts in a car and the base of the fire is 0.5 m above floor level. Fire grows at fast t^2 rate.	
2	Smoke spreads within B2 and into B1 through car ramp.	Stairway door is closed.	Rate and quantity of smoke determined via fire modeling.
3	Thermal alarm in car park activates and warning sounds throughout building.	Thermal alarm in car park located 7 m from fire 25 mm below the ceiling and will activate at 57ºC.	Activation determined via fire modeling.
4	Occupants in the car park prepare to evacuate.	30 sec pre-movement activity time for B2 and 60 sec for B1.	

No.	Event	Assumptions	Comments
5	The occupants evacuate through the stairway and fully open the stairway door during evacuation. Stairway door is closed after occupants have moved through them.	Assume that all of the occupants use the stairway for evacuation and not the ramp.	Duration of the door being opened is determined from evacuation analysis. Quantity of smoke flow through open door is determined vi fire modeling.
6	Fire in car park continues to grow.	Car park load density = 900 MJ/m^2 (to check). Max HRR is 20 MW. No failure of the building structure occurs.	Fire may grow to flashover or become ventilation or fuel limited as determined by the fire modeling.
7	Evacuation paths in the building affected by the fire.	Conditions of the egress paths monitored at various locations along the egress path.	Conditions are determined via fire modeling and checked against tenability criteria.

Table 5-6: Assumed sequence of events according to the FPA report.

5.1.7 CF2 – Challenging Fire in Retail Area

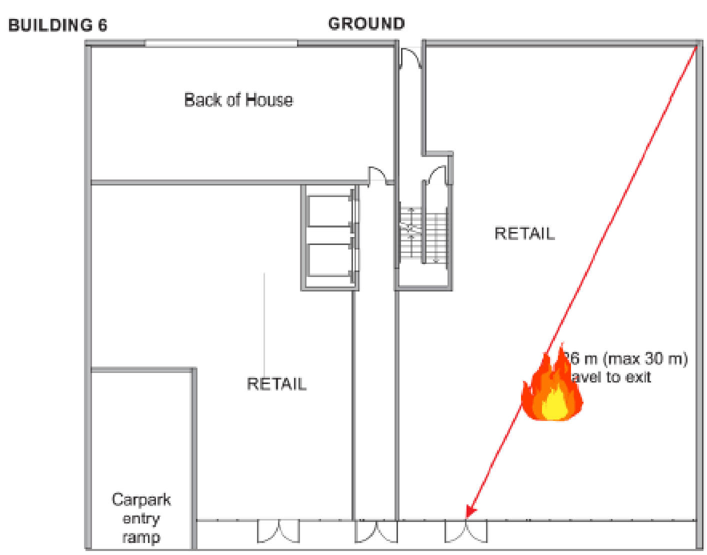


Figure 5-7: Location of the design fire in the CF2 scenario on the ground floor.

Assumed sequence of events according to the FPA report:

No.	Event	Assumptions	Comments
1	Fire starts in retail area (see Figure 5-7).	Building fully occupied. Fire grows at fast t^2 rate. Fire load density = 900 MJ/m^2.	
2	Smoke detector in retail area activates and warning sounds throughout the building.	Smoke detector is located 7 m from the design fire, 25 mm below the ceiling and will activate at 0.14/m optical density.	Detection time determined via fire modeling.
3	Occupants in the building prepare to evacuate.	60 sec pre-movement activity time.	
4	The occupants in the retail area evacuate directly to the outside through the exit in front of the retail areas. The exit doors in the retail area are left open.	Exit doors in retail areas are not fitted with a self-closure.	
5	Evacuation paths in the building affected by the fire.	Conditions of the egress paths monitored at various locations along the egress path.	Conditions are determined via fire modeling and checked against tenability criteria.

Table 5-7: Assumed sequence of events according to the FPA report.

5.1.8 CF3, CF4 & CF5 – Challenging Fires in office area

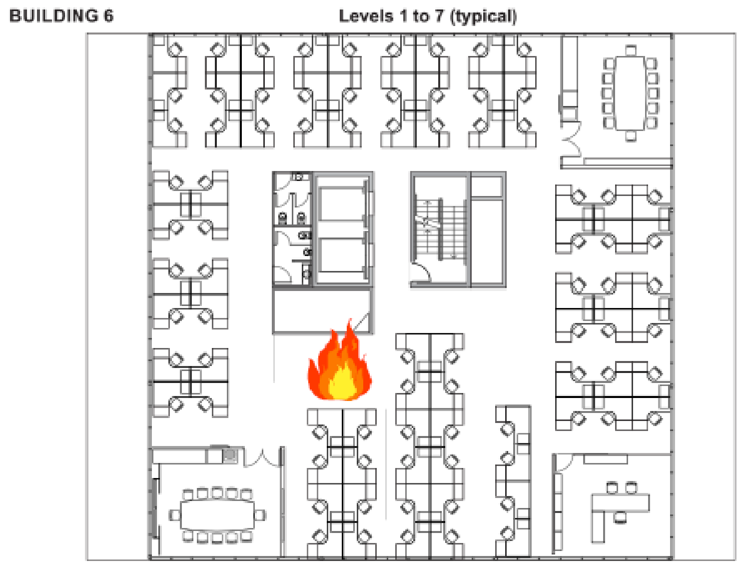


Figure 5-8: Location of design fire in the CF3, CF4 & CF5 scenarios on the office floors.

Assumed sequence of events according to the FPA report:

No.	Event	Assumptions	Comments
1	Fire starts in an office area (CF3, CF5) or library (CF4) (see Figure 5-8).	Building fully occupied. Fire grows at fast t^2 rate. Fire load density for CF3 and CF5 = 570 MJ/m^2. Fire load density for CF4 = 2250 MJ/m^2.	
2	Smoke detector in retail area activates and warning sounds throughout the building.	Smoke detector is located 7 m from the design fire, 25 mm below the ceiling and will activate at 0.14/m optical density.	Detection time determined via fire modeling.
3	All occupants in the building prepare to evacuate.	60 sec pre-movement activity time.	
4	All occupants commence movement at the same time and move into stairway or out of the building.	Travel speeds and flow rates as assumed in evacuation modeling.	Evacuation times determined via evacuation analysis.

No.	Event	Assumptions	Comments
5	Stairway doors on all floors open while occupants move or queue at stairway entries.	Stairway doors open during evacuation.	Queuing time determined via evacuation analysis.
6	Smoke spread into stairway and other parts of building via open stairway doors (CF5 smoke also spread from L6 to L7 via the floor void containing open stairway)	Travel speeds and flow rates as assumed in evacuation modeling. (CF5 assumes occupants do not use the open stairway for evacuation purposes)	
7	Evacuation paths in the building affected by the fire.	Conditions of the egress paths monitored at various locations along the egress path.	Conditions are determined via fire modeling and checked against tenability criteria.

Table 5-8: Assumed sequence of events according to the FPA report.

5.1.9 RC1-RC10 – Robustness Check

The intention of the robustness check is to make sure that a failure of a critical part of the fire safety systems will not result in the building design not meeting the required level of fire safety. Therefore the design fire in this scenario will have the same characteristics and location as the design fire in the CF-scenarios. In addition to this, a fire safety system will be assumed to malfunction for each of the RC scenarios:

- RC1-RC5: Failure of self-closers of stairway doors;
- RC6- RC10: Failure of automatic detection and occupant warning system.

5.1.10 SS – Structural Stability Check

The structural stability of the building is calculated using the time-equivalent formula for full burnout design fires proposed by the VM. Then the results were compared with the fire resistance levels of the structural elements in the area. Therefore the SS scenario does not require an ASET/RSET analysis.

5.1.11 IS2 – Fire Spread involving Internal Finishes

The required performance criteria for the lining materials within the building will depend on their location within the building. The design scenario is passed, when the provision of linings is in compliance with the BCA's DtS provisions. An ASET/RSET analysis is not required for this scenario.

5.1.12 HS1 & HS2 – Horizontal Fire Spread

HS1 deals with a fully developed fire in the office area near an external wall. This fire emits a heat flux to and over a boundary located 3 m into an adjacent property. The emitted heat flux is calculated and kept below heat flux limits set by the VM in order to prevent fire spread to adjacent properties via radiation.

The HS2 scenario refers to a fully developed fire in an adjacent property, which can spread to the building through radiation. The heat flux emitted to the boundary from an assumed opening located 3 m into the adjacent property is calculated. This heat flux must be lower than the limits presented in the VM.

An ASET/RSET analysis is not required for the HS scenarios.

5.1.13 VS – Vertical Fire Spread

It must be demonstrated that the building's external wall make up and penetrations do not contribute to excessive vertical fire spread. The expected method to comply with this scenario is to use suitable materials and specified construction features that are required to limit vertical fire spread.

5.1.14 FI1 – Fire Brigade Intervention

In order to comply with this scenario, the Australasian Fire and Emergency Service Authorities Council's Fire Brigade Intervention Model must be applied. In addition, a list of facilities for firefighting facilities must be provided in accordance with the VM. An ASET/RSET analysis is not required for this scenario.

5.1.15 Results

In all, 27 design scenarios in the building were identified and analyzed. A summary of the results from the FPA report is provided in Table 5-9.

<table>
<tr><th>Scenario</th><th colspan="7">Results</th></tr>
<tr><td>BE – Fire Blocks Exit</td><td colspan="7">BE1: Fail – This scenario is not explicitly modeled as the office area contains only one exit and the occupants would be trapped in the event of a fire blocking the single exit.</td></tr>
<tr><td rowspan="4">UT - Fire in Unoccupied Room</td><td>ID</td><td>Location</td><td>Min. ASET</td><td>Max. RSET</td><td>ASET/RSET</td><td>Pass/Fail</td><td>Fatalities</td></tr>
<tr><td>UT1</td><td>Office</td><td>150</td><td>177</td><td>0.85</td><td>F</td><td>27</td></tr>
<tr><td>UT2</td><td>Retail</td><td>160</td><td>175</td><td>0.91</td><td>F</td><td>70</td></tr>
<tr><td colspan="7">Overall failure occurs when occupants do not have sufficient time to move out of floor or enclosure of fire origin.</td></tr>
<tr><td rowspan="3">CS – Con-cealed Space Fire</td><td>ID</td><td>Location</td><td>Min. ASET</td><td>Max. RSET</td><td>ASET/RSET</td><td>Pass/Fai l</td><td>Fatalities</td></tr>
<tr><td>CS1</td><td>Office</td><td>100</td><td>182</td><td>0.55</td><td>F</td><td>62</td></tr>
<tr><td colspan="7">Overall failure occurs when occupants do not have sufficient time to move out of floor of fire origin.</td></tr>
</table>

Scenario	Results						
SF – Smoldering Fire	N/A – This scenario is not applicable given that there is no sleeping accommodation provided in this building.						
IS - Internal Finishes Fire	IS1: Pass IS2: Pass Based on the provision of linings in compliance with the BCA DtS Provisions.						
CF - Challenging Fire	ID	Location	Min ASET	Max RSET	ASET/RSET	Pass/Fail	Fatalities
	CF1	Car park	85	145	0.57	F	118
	CF2	Retail	95	180	0.51	F	120
	CF3	Office (L7)	100	182	0.55	F	114
	CF4	Office (Library)	110	182	0.60	F	61
	CF5	Office (L6)	125	182	0.69	F	66
	Overall failure occurs when occupants do not have sufficient time to move out of floor or enclosure of fire origin.						
RC - Robustness Check	ID	Location	Min ASET	Max RSET	ASET/RSET	Pass/Fail	Fatalities
	RC1	Car park	270 [215]	236	0.91	F	21
	RC2	Retail	95	180	0.51	F	120
	RC3	Office (L7)	100	236	0.42	F	62
	RC4	Office (Library)	280 [255]	236	0.84	F	11
	RC5	Office (L6)	205	236	0.87	F	31
	RC6	Car Park	270 [215]	361	0.59	F	62
	RC7	Retail	95	180	0.51	F	120
	RC8	Office (L7)	100	231	0.43	F	62
	RC9	Office (Library)	280 [255]	366	0.70	F	62
	RC10	Office (L6)	205	321	0.64	F	62
	Robustness checks were conducted on failure of fire doors associated with the compartment of fire origin. Overall failure occurs where occupants do not have sufficient time to move out of floor of fire origin and other floors due to the provision of single fire isolated exit. Brackets indicate ASETs for staircases.						

<table>
<tr><th>Scenario</th><th colspan="4">Results</th></tr>
<tr><td rowspan="6">SS - Structural Stability</td><td>Area</td><td>FRL provided</td><td>Time equivalence (min)</td><td>Pass/Fail</td></tr>
<tr><td>Car Park</td><td>120/120/120</td><td>310</td><td>F</td></tr>
<tr><td>Retail</td><td>180/180/180</td><td>112</td><td>P</td></tr>
<tr><td>Office</td><td>120/120/120</td><td>83</td><td>P</td></tr>
<tr><td>Office + Library</td><td>120/120/120</td><td>101</td><td>P</td></tr>
<tr><td colspan="4">FRLs provided are greater than the time equivalence for all areas except the car park. The car park has a relatively small ventilation area and it is outside the range for the time equivalence equation and the lower limit applicable for the equation was adopted. Also, the design fire load for car park is not given in the proposed VM and is assumed to equal that for shops (900 MJ/m2). Both these factors resulted in a significantly high time equivalence for the car park.</td></tr>
<tr><td rowspan="7">HS - Horizontal Fire Spread</td><td colspan="4">HS1: Heat flux emitted are:</td></tr>
<tr><td>Distance [m]</td><td>CV1 criteria [kW/m^2]</td><td>Heat flux [kW/m^2]</td><td>Pass/Fail</td></tr>
<tr><td>Boundary</td><td>80</td><td>52.97</td><td>P</td></tr>
<tr><td>1</td><td>40</td><td>40.88</td><td>F</td></tr>
<tr><td>3</td><td>20</td><td>27.32</td><td>F</td></tr>
<tr><td>6</td><td>10</td><td>17.32</td><td>F</td></tr>
<tr><td colspan="4">HS2: Pass
Heat flux received (HS2) at the glazed openings is calculated to be 15.6 kW/m2. It is assumed that the glazing could withstand the heat flux without causing fire spread</td></tr>
<tr><td>VS – Vertical Fire Spread</td><td colspan="4">Pass – Based on non-combustible facades being assumed.</td></tr>
<tr><td>FI - Fire Brigade Intervention</td><td colspan="4">FI1: Fail
The building is not equipped with an automatic notification of Fire Brigade and timeline for Fire Brigade Intervention is indeterminate.</td></tr>
<tr><td>UF – Unexpected Catastrophic Failure</td><td colspan="4">No detailed structural design has been carried out, however, the structure is in accordance with the DtS Provisions of NCC 2016.</td></tr>
</table>

Table 5-9: Summary of results from the FPA report.

The results in Table 5-9 show that 22 of designs scenarios failed the requirements of the Verification Method. These scenarios are:

- BE1
- UT1 & UT2
- CS1
- CF1, CF2, CF3, CF4 & CF5
- RC1, RC2, RC3, RC4, RC5, RC6, RC7, RC8, RC9 & RC10
- SS
- HS1
- FI1

The design failed all of the scenarios that required an ASET/RSET analysis, meaning that in no case was the ASET high enough for the occupants to escape in time. The only scenarios that passed were the internal finishes and vertical fire spread scenarios as these are based on the DtS provisions of the BCA.

5.2 Reevaluation of Failed Design Scenarios

The original design of the building cannot be verified for compliance and will therefore have to be adjusted in order to pass these design scenarios. Changes for the buildings will thus be proposed, followed by new evaluations of the design scenarios. The assumptions used for the new application of the Verification Method will be similar to those made in the FPA report with minor changes. The new assumptions are listed in section 5.1.1. The scenarios will be sorted after occupancy category so that all scenarios related to the car park will be dealt with, followed by all scenarios relevant to the ground floor and lastly all scenarios relevant to the upper floors. The FI scenario is general for the entire building.

Because none of the retail area is connected to the staircase, the RC2 does not need to be explicitly modeled. The RC2 scenario will yield the same results as for the CF2 design scenario. The same goes for the RC3 scenario, as it deals with the failure of self-closing doors and the impact that it will have on other evacuating floors. As the RC3 scenario takes place on the top floor, there is assumed no smoke spillage to the staircases that will impact lower evacuating floors.

In the original report, the scenarios RC6 through RC10 were meant to ensure the robustness of the fire safety design of the building in case of failure of the automatic detection and occupant warning system. However, failure of the self-closing fire safety doors was also included in these scenarios, which resulted in very conservative results. The RC6 - RC10 scenarios in this report will therefore be modeled with closed doors, leading to the same ASETs calculated in the corresponding CF-scenarios. However, the RSETs will change as the detection will happen manually instead of automatically.

The new calculations for all scenarios can be found in Appendix C. Equations, references, formulae and sample calculations for the RSET manual calculations are described in detail in Appendix D. Calculations, equations, references, formulae and sample calculations for the ASET zone modeling are described in detail in Appendix E.

5.3 Results

The reasons that the original design of the building failed the Verification Method scenarios were identified, before an alternate design solution was proposed. Then the

Verification Method was applied to the new solutions in order to verify their compliance. This application of the Verification Method resulted in the following new design solutions for the car park, the retail space and the office floors.

Car Park (B1 & B2):

It was found that for the car park, the ASET was not sufficient for adequate egress. A means to enhance the ASET to an adequate level can be done by equipping the basement with a voice alarm signal and enhancing the free width of the single exit and the stairway from 0.75 to 1.10 m from the basement to the ground floor. Additionally, the ceiling height must be increased from 2.5 m to 2.9 m.

The fire resistance ratings were inadequate for the structures in the car park due to the high time equivalence being calculated to 310 min. The maximum fire resistance rating available in Australia of FRL240/240/240 can be provided instead.

Retail Space (Ground Floor):

It was found that for the car park, the ASET was not sufficient for adequate egress. A means to enhance the ASET to an adequate level can be done by providing each of the two stores with either of the following solutions:

(a) 2 exits with clear widths of 1.50 m, a standard alarm signal, an unchanged ceiling height of 3.0 m and a smoke control system.
(b) 3 exits with clear widths of 2.30 m, a voice alarm signal and an increased ceiling height of 3.7 m.

Each of the design solutions have been demonstrated for one exit less, but an additional exit is needed in order to comply with the BE2 design scenario.

Office Floors (L1-L7):

It was found that for the car park, the ASET was not sufficient for adequate egress. A means to enhance the ASET to an adequate level can be done by providing each of the office floors with either of the following solutions:

(a) 2 exits and staircases with clear widths of 1.20 m, a voice alarm signal, and an increased ceiling height of 3.1 m

(b) 3 exits and staircases with clear widths of 1.40 m, a voice alarm signal and an unchanged ceiling height of 2.7 m

Each of the design solutions have been demonstrated for one exit less, but an additional exit is needed in order to comply with the BE1 design scenario.

Results

The Verification Method has been applied to the proposed building design alterations mentioned above which were expected to enhance the ASETs sufficiently. In Table 5-10, a summary of results from the application of the design scenarios to the proposed designs is provided. The full set of results and calculations of the application can be found in Appendix C.

<table>
<tr><th>Scenario</th><th colspan="7">Results</th></tr>
<tr><td rowspan="1">BE – Fire Blocks Exit</td><td colspan="7">BE1: Pass
BE2: Pass
These scenarios passed because of the addition of a second/third exit to the retail areas and an additional staircase leading from the upper floors to the ground floor.</td></tr>
<tr><td rowspan="4">UT - Fire in Unoccupied Room</td><td>ID</td><td>Location</td><td>Min. ASET</td><td>Max. RSET</td><td>ASET/RSET</td><td>Pass/Fail</td><td>Fatalities</td></tr>
<tr><td>UT1</td><td>Office</td><td>160</td><td>124</td><td>1.29</td><td>P</td><td>0</td></tr>
<tr><td>UT2</td><td>Retail</td><td>180</td><td>170</td><td>1.06</td><td>P</td><td>0</td></tr>
<tr><td colspan="7">Overall failure occurs when occupants do not have sufficient time to move out of floor or enclosure of fire origin.</td></tr>
</table>

Scenario	Results						
CS – Concealed Space Fire	ID	Location	Min. ASET	Max. RSET	ASET/RSET	Pass/Fail	Fatalities
	CS1	Office	100	97	1.03	P	0
	Overall failure occurs when occupants do not have sufficient time to move out of floor of fire origin.						
IS - Internal Finishes Fire	IS1: Pass IS2: Pass Based on the provision of linings in compliance with the BCA DtS Provisions.						
CF - Challenging Fire	ID	Location	Min ASET	Max RSET	ASET/RSET	Pass/Fail	Fatalities
	CF1	Car park	110	107	1.03	P	0
	CF2	Retail	115	100	1.05	P	0
	CF3	Office (L7)	100	97	1.03	P	0
	CF4	Office (Library)	125	124	1.01	P	0
	CF5	Office (L6)	130	124	1.05	P	0
	Overall failure occurs when occupants do not have sufficient time to move out of floor or enclosure of fire origin.						
RC - Robustness Check	ID	Location	Min ASET	Max RSET	ASET/RSET	Pass/Fail	Fatalities
	RC1	Car park	215	213	1.01	P	0
	RC2	Retail	115	100	1.05	P	0
	RC3	Office (L7)	-	-	-	P	0
	RC4	Office (Library)	210	203	1.04	P	0
	RC5	Office (L6)	240	203	1.18	P	0
	RC6	Car Park	110	107	1.03	P	0
	RC7	Retail	115	100	1.05	P	0
	RC8	Office (L7)	100	97	1.03	P	0
	RC9	Office (Library)	125	124	1.01	P	0
	RC10	Office (L6)	130	124	1.05	P	0
	Robustness checks were conducted on failure of fire doors associated with the compartment of fire origin (RC1-RC5) and failure of the automatic detection and occupant warning system (RC6-RC10). Overall failure occurs where occupants do not have sufficient time to move out of floor of fire origin and other floors.						

<table>
<tr><th>Scenario</th><th colspan="5">Results</th></tr>
<tr><td rowspan="6">SS - Structural Stability</td><td>Area</td><td>FRL provided</td><td colspan="2">Time equivalence (min)</td><td>Pass/Fail</td></tr>
<tr><td>Car Park</td><td>240/240/240</td><td colspan="2">310</td><td>P</td></tr>
<tr><td>Retail</td><td>120/120/120</td><td colspan="2">112</td><td>P</td></tr>
<tr><td>Office</td><td>90/90/90</td><td colspan="2">83</td><td>P</td></tr>
<tr><td>Office + Libary</td><td>120/120/120</td><td colspan="2">101</td><td>P</td></tr>
<tr><td colspan="5">FRLs provided are greater than time equivalence for all areas.
The car park has a relatively small ventilation area and it is outside the range for the time equivalence equation and the lower limit applicable for the equation was adopted. Also, design fire load for car park is not given in the proposed VM and is assumed to equal that for shops (900 MJ/m2). Both these factors resulted in a significantly high time equivalence for the car park.</td></tr>
<tr><td rowspan="7">HS - Horizontal Fire Spread</td><td colspan="5">HS1: Heat flux emitted are:</td></tr>
<tr><td>Distance [m]</td><td>View factor</td><td>Heat flux [kW/m^2]</td><td>CV1 criteria [kW/m^2]</td><td>Pass/Fail</td></tr>
<tr><td>Boundary</td><td>0.179</td><td>24.05</td><td>80</td><td>P</td></tr>
<tr><td>1</td><td>0.153</td><td>20.48</td><td>40</td><td>P</td></tr>
<tr><td>3</td><td>0.114</td><td>15.28</td><td>20</td><td>P</td></tr>
<tr><td>6</td><td>0.080</td><td>10.71</td><td>10</td><td>P</td></tr>
<tr><td colspan="5">HS2: Pass
Heat flux received (HS2) at the glazed openings is calculated to be 15.6 kW/m2. It is assumed that the glazing could withstand the heat flux without causing fire spread</td></tr>
<tr><td>VS – Vertical Fire Spread</td><td colspan="5">Pass – Based on non-combustible facades being assumed.</td></tr>
<tr><td>FI - Fire Brigade Intervention</td><td colspan="5">FI1: Pass
The building is equipped with facilities for firefighting and the timeline for Fire Brigade Intervention is determinate.</td></tr>
<tr><td>UF – Unexpected Catastrophic Failure</td><td colspan="5">No detailed structural design has been carried out, however the structure is in accordance with the DtS Provisions of NCC 2016.</td></tr>
</table>

Table 5-10: Summary of results from the reevaluation of the design scenarios. The full set of results and calculations can be found in Appendix C.

Chapter 6 Results, Critique & Future Work

6.1 Results

Five different fire safety design approaches have been applied to the building, resulting in a number of different design solutions. The solutions vary in egress provisions, fire safety systems, detection and alarm systems, geometry etc. A summary of the results can be seen in Table 6-1, Table 6-2 and Table 6-3 below.

Unlike all of the prescriptive design solutions, the Verification Method, like the PBD solutions, allows for different design solutions, proving its superiority in flexibility to the prescriptive codes. However, when compared to the Performance-based designs, the VM provides narrower or broader exits and either too many of them or too few in many cases. The VM increases the level of fire safety of BCA by requiring more than one exit in the retail areas per the BE-scenario, which compared to the remaining designs is an adequate requirement. Despite the fact that VM solution 1 requires one more exit than the PBDs for the retail space, the ceiling height will have to be increased with 20 cm more than the PBD solution 2 had to be in order to achieve an acceptable RSET/ASET rate. On top of the taller floor-to-ceiling height, a voice alarm system is also required. If the third exit, the increased ceiling height and the voice alarm system were to be avoided for the ground floor, VM solution 2 must be chosen, which is the sole design solution to require a smoke control system on the ground floor. Generally, the different design solutions for the retail, car park and office areas indicate that the VM over benefits the building.

The VM provides either the same or a higher level of life safety than the prescriptive codes in regards to egress provision and detection and alarm systems. However, training of the staff in the retail or office area, which would enable them to instruct other occupants in the event of an emergency, is not addressed in the VM, leading to a slower RSET. Additionally, the time equivalence method used in the VM results in the lowest fire resistance ratings required by any of the design solutions in the retail space.

The Verification Method offers more flexible design options than the prescriptive codes and generally requires a lower level of engineering than the Performance-Based Design Method. However, the lower level of engineering may result in the building being under-designed or over-designed in certain areas as those described above.

	Prescriptive Building Designs			Performance-Based Designs		Verification Method Designs	
	AU Solution	**USA Solution**	**UK Solution**	**PBD Solution 1**	**PBD Solution 2**	**VM Solution 1**	**VM Solution 2**
Occupant density	3 m^2/person	2.8 m^2/person	2 m^2/person	2 m^2/person	2 m^2/person	3 m^2/person	3 m^2/person
Number of exits per store	2 (1 double-door)	2	2	2	2	3	2
Clear door widths [m]	0.75 (1.50)	0.81	0.75	1.70 – 2.10	1.70 – 2.10	2.30	1.50
Floor-to-ceiling height [m]	3	3	3	3	3.5	3.7	3.0
Automatic smoke detection and alarm system	Yes	Yes	No (Only manual alarm system)	Yes	Yes	Yes	Yes
Alarm signal	Standard	Standard	Standard	Standard	Standard	VAS	Standard
Heat detectors	No	No	No	No	No	No	No
Sprinklers	No	Yes	No	No	No	No	No
Smoke control system	No	No	No	No	No	No	Yes
Fire resistance rating of structures [minutes]	180	180	90 (elevator shaft: 120)	240	200	120	120
Required training of staff	Yes	Yes	Yes	Yes	No	No	No

Table 6-1: Summary of results for ground floor (Retail space). VAS = Voice Alarm Signal

	Prescriptive Building Designs			Performance-Based Designs	Verification Method Designs
	AU Solution	**USA Solution**	**UK Solution**	**PBD Solution 1**	**VM Solution 1**
Occupant density [pers/level]	25	17	28	28	25
Number of exits per story	1 + Ramp	1 + Ramp	1 + Ramp	1 + Ramp	1 + Ramp
Clear door widths [m]	0.75	0.81	0.75	1.10	1.10
Clear stairway widths [m]		1.25	1.0	1.10	1.10
Floor-to-ceiling height [m]	2.5	2.5	2.5	2.75	2.90
Automatic smoke detection and alarm system	No	Yes	Yes	Yes	Yes
Automatic heat detection and alarm system	Yes	No	No	No	No
Alarm signal	Standard	Standard	Standard	Standard	Voice alarm signal
Sprinklers	No	Yes	No	No	No
Smoke control system	No	Yes (Stairwell pressurization)	Yes (Mechanical ventilation and stairwell pressurization)	Yes (Stairwell pressurization)	No
Fire resistance rating of structures [minutes]	120	120	90	200	310

Table 6-2: Summary of results for the basement (Car parking space).

	Prescriptive Building Designs			Performance-Based Designs		Verification Method Designs	
	AU Solution	**USA Solution**	**UK Solution**	**PBD Solution 1**	**PBD Solution 2**	**VM Solution 1**	**VM Solution 2**
Occupant density	10 m^2/person	9.3 m^2/person	6 m^2/person	6 m^2/person	6 m^2/person	10 m^2/person	10 m^2/person
Number of exits per story	1	2	2	2	2	3	2
Clear door widths [m]	0.75	0.81	0.85	1.6	1.6	1.4	1.2
Clear stairway widths [m]	1.0	1.25	1.0	1.6	1.6	1.4	1.2
Floor-to-ceiling height [m]	2.7	2.7	2.7	3.1	3.5	2.7	3.1
Automatic smoke detection and alarm system	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Alarm signal	Standard	Standard	Standard	Standard	Standard	VAS	Standard
Heat detectors	No	No	No	No	No	No	No
Sprinklers	No	Yes	No	No	No	No	No
Smoke control system	No	Yes (Stairwell pressurization)	Yes (Stairwell pressurization)	Yes (Stairwell pressurization)	Yes (Stairwell pressurization)	No	No
Fire resistance rating of structures [minutes]	120	120	90	170 (L2-L7) 380 (L1)	170 (L2-L7) 380 (L1)	90 (L2-L7) 120 (L1)	90 (L2-L7) 120 (L1)
Required training of staff	Yes	Yes	Yes	Yes	No	No	No

Table 6-3 Summary of results for level L1 – L7 (Office and library area). VAS = Voice Alarm Signal.

6.2 Critique

The Verification Method was created as a means to provide designers, fire engineers and building consent authorities with better design criteria so that the resulting fire designs would be more consistent. Upon the application of a performance based design method, specification-based prescriptive codes and finally the Verification Method onto the same case building, a number of advantages and weaknesses of the VM has been identified. These will be listed in this section.

6.2.1 Perceived or Desired Advantages

- *Time efficiency*

Developing the performance criteria and design fire scenarios in a PBD is complex, time-consuming and often results in uncertain outcomes as a fire event is hard to predict. With the VM, the time to complete the fire safety design of a building is significantly reduced compared to the time it takes to conduct and review a performance-based design. Subsequently, it is also easier to adjust the features of the building during the design-phase.

- *Enhancement of certainty in compliance*

Demonstrating compliance with the building codes yields less uncertainty than a performance-based design. The prescriptive methods provide specific regulations for complying with the building codes, while the performance criteria for a PBD must be developed by the designer herself/himself, which consequently leads to a higher degree of uncertainty. The VM is a tool created to make the process of complying with the BCA more see-through and thereby reduce the uncertainty succeeding the use of PBD.

- *Accessibility*

A lower level of engineering and expertise is required to perform a Verification Method design compared to a PBD. The application of PBD requires a high level of expertise and understanding of the building and fire events. If the designer lacks the necessary knowledge and experience that PBD requires, the design solution will become more uncertain. The VM provides prescribed values and guidelines in areas that would normally require a high level of engineering, such as developing performance criteria and design fire scenarios. Although the engineering level is lower than for PBD, it is higher than the one required when applying prescriptive codes, which also promotes a better understanding of how a building would perform during a fire.

- *Flexibility*

The Verification Method offers more flexibility in its final solutions than the prescriptive codes. Often the prescriptive codes will result in only one acceptable solution as a list of minimum requirements will have to be satisfied, e.g. the NFPA codes would still require fire suppression systems to be installed, although an alternative fire safety system were to be added or more exits were to be provided. The flexibility is pronounced as there is more than one design solution when the Verification Method is applied to the building.

6.2.2 Observed Weaknesses

- *Substitution of the designer*

The most significant weakness of the Verification Method is possibly that by trying to substitute the designer, it creates a hybrid of performance-based and prescriptive methods that will never work. A VM should be a tool that solely simplifies compliance approval so that if the design is verified by this method, the authority's job of reviewing the design becomes easier. This is the true objective of a Verification Method, which is not easy to accomplish, but it is achievable. However, substitution of the designer is not viable, unless a fully prescriptive approach is chosen so that a solution is defined for each classification.

- *Over-design of buildings*

The increased level of fire safety in certain aspects is due to over-design of the building. Over-design will result in cost-inefficient solutions and a building design that is harder to construct and/or maintain. E.g. a smoke exhaust system like the one required in VM solution 2 for the ground floor increases the ASET, but is definitely more expensive and time-consuming to incorporate and maintain in a building, both in the design-phase and during the construction of the actual building.

- *Under-design of buildings*

In some aspects, the Verification Method promotes lower requirements to the level of fire safety than both the prescriptive methods and the Performance-based design method, resulting in under-design of the building. These areas include the structural stability of the building, the fire safety management requirements and clear widths of exits. Under-design can possibly lead to casualties during a fire event, which is unacceptable.

- *Lack of robustness*

The lack of safety factors and robustness of the prescribed values for the performance criteria, design fires and occupant characteristics needs to be addressed. A substantial part of the PBD process was determining the robustness of the developed performance criteria and reevaluating them. As the VM prescribes the performance criteria from the beginning, no reevaluation is required and all values are treated as universally applicable. This type of under-engineering of the fire safety design results in the lack of a safety factor between the ASET and the RSET. For the RC7 for the VM solution 2, the RSET was calculated to 110 sec, while the ASET was 111 sec, only leaving 1 sec of difference. This means that a safety buffer for this solution is inexistent, leaving no extra time for occupants to evacuate, should any of the assumptions of the VM prove to be insufficient. A simple way to account for the under-engineering in the VM design is to implement safety factors to the evacuation time or the performance criteria. The VM doesn't require the designer to address these issues with the prescribed performance criteria, which will result in the building becoming under-designed.

Also, the Verification Method fails to address the robustness of the prescribed deterministic values that it provides. There are no safety buffers included for occupants that e.g. are taller than 2.0 m, walk at a slower pace than the average occupant, or if the occupant load should prove to be less than 3.0 m^2/person at the event of a fire. If the Verification Method is determined to maintain prescribed fixed values for factors that in reality are not deterministic, such as human behavior, guidance on how to estimate the actual robustness of the design must be included in the VM. Without the safety buffers, unacceptable causalities are bound to occur.

- *Too generic assumptions*

The Verification Method is devised in such a way that it provides strong guidance for general buildings rather than specific occupancies. When applying prescriptive methods, building types are often divided into different occupancies which will have different requirements as the function of the building varies with the occupancy. Especially the design fires available in the VM lack diversity. For the retail space, the category "all building with a stack height of maximum 3.0 m" was applicable, although it doesn't differ between the possible fuel loads in a retail space and all other types of occupancies. The peak HRR in the VM is very high, but the smaller fire growth rate led to less severe fire characteristics than those computed in the PBD. Generally in the PBD, the design fires for the different occupancies varied considerably. The Verification Method ought to incorporate more diverse values, allowing for more specified design options based on occupancy types.

- *Certain areas fail to be addressed*

An issue of the pre-defined performance criteria in the VM is that they fail to address several areas that potentially could have importance for specific design, e.g. the human intolerance to toxicity levels in the smoke layer. The tenability parameters are measured at a height of 2.0 m above the floor, which is not the same as assuming a minimum smoke layer height of 2.0 m. The performance criteria technically allow for humans to be exposed to toxic combustion products, as long as the visibility and thermal criteria are not exceeded. In the performance-based design, the issue of toxicity was handled by assuming a minimum smoke layer height above head-height. Another issue is the visibility criterion. The criterion is only concerned with the visibility 2.0 m above the floor, but its validity is questioned if the exit signs are mounted above 2.0 m above the floor, which is the case in most buildings.

Furthermore, the VM does not mention any need for fire safety management training.

- *Lack of guidance for type of fire model*

Because the Verification Method doesn't set up any limitations as to what fire model to use, the designer has all options open and can therefore select either a zone model, a field model or manual calculations. However, the VM does not provide any guidance on what model to choose either. While a zone model may be preferred in many cases, it is not applicable to all situations. E.g. when modeling smoke movement into the staircase from the office floors, the CFAST model indicated that the smoke layer in the stairwell shaft would fall very rapidly, despite the fact that the layer height had not fallen below door height level. These results meant that the CFAST model could not be applied, when the performance criteria revolved around the smoke layer height and the model included a shaft. So, while certain parameters are specified in great detail (E.g. design fires), others are left fully to the engineer to judge (E.g. model type). The choice of model is many times a more complex process than the choice of design fire.

There is a strong coherence between the choice of fire model and the developed performance criteria, which must be appropriate to the model being used for the analysis.

The comparison study in this project revealed that the criteria developed in the PBD were not appropriate for evaluation in FDS without expert input as the outcomes in FDS are spatially distributed and not lumped. Comparison studies conducted by Fire Protection Association Australia concluded that the tenability criteria defined by the VM are not appropriate for FDS results as it leads to unacceptable error bars associated to spatial distribution of smoke. Especially the visibility criterion required extensive expert analysis when being evaluated in an FDS model. The averaged nature of zone models is consistent with many of the performance criteria. The Verification Method does not offer any guidance that will restrain the poor use of the FDS results.

- *Lack of guidance for defining fire model input and treating fire model output*

Both zone models and field models require several types of input. Although a list of fire modeling assumptions is available in the VM, it fails to define numerous fire characteristics that are needed when creating a fire model. In order to determine these characteristics without guidance, the level of engineering needs to be equal to the one achieved in the PBD. Examples of the characteristics include:

- The fire area: The peak fire area, and the time evolution of the area.
- The chemical combustion reaction: Fire models require chemical fuel input, which are not defined by the VM.
- The CO-yield: An important input in CFAST impacting the smoke layer characteristics.
- HRRPUA which is a parameter used by FDS.

- Heat transfer to solid boundaries: The heat transfer to the solid boundaries depend on what materials they are made of. No guidance on how to build the solid boundaries is provided in the VM.
- Grid sizes in CFD models.

In addition to the lack of these characteristics, there is no guidance when it comes to choosing from the range of values for the fire growth and the peak HRR. This would lead to the highest values being chosen in many cases, but it also means that it is allowed to choose the lower limit value although it could result in under-design of the building.

In general, the more sophisticated the fire model is, the more inputs are necessary and the more complicated it will be to define them, and the VM is lacking input information for even simple models. The input will affect the output from the models, in many cases significantly. Sophisticated models will also yield a wider range of output, such as the spatially distributed results from FDS, which may entail further necessary guidance on how to analyze the data. Such guidance is not provided in the VM.

- *Potential risk of causing over-engineering*

In the Verification Method, 12 various design scenarios have been established, and the designer is under no obligation to consider any other scenarios than those provided in the VM. However, the need for evaluating all of the scenarios in order to comply with the building code may cause over-engineering. The UT scenario (Fire in a normally unoccupied room) requires an ASET/RSET analysis to be carried out, possibly using the same design fire as for the CF scenario (challenging fire). As expected, the execution of the UT scenario showed that the ASET for the occupants was longer, when the design fire was placed in the small, unoccupied storage room instead of in the larger, occupied space. An ASET/RSET analysis should only be required for this scenario if a more severe design fire was to be assumed in the unoccupied space than in the adjacent space. Otherwise it should be sufficient to require an automatic detection system in the unoccupied space without performing an ASET/RSET analysis.

- *Uncertain Fire Resistance Rating Calculations*

The Verification Method proposes a time equivalence formula taken from Eurocode 1 for determination of fire resistance ratings. It was discussed how small ventilation areas and high fuel loads will yield very high time equivalences due to the uncertain and oversized fire curves specifications. The high time equivalences will prompt the designer to explore options to reduce the calculated time equivalence, which can be done through increasing the ventilation area or applying reduction factors to the fuel load. Both these methods induce uncertain results. The Verification Method therefore encourages uncertain methods for fire resistance calculation, particularly by using reduction factors as these are provided directly in the VM.

Additionally, the fuel loads prescribed for the post-flashover fires vary significantly depending on the type of occupancy. In the PBD chapter, design fire loads specified in the *International Fire Engineering Guidelines 2005* (IFEG) [21] were assumed. The VM defines its own design fire loads, which are also extracted from the IFEG. However, in the PBD, the fuel loads were for the 95th percent fractile, while in the

VM they are for the 80^{th} percent fractile. Therefore the fire resistance of the structures may be underscaled when applying the VM.

6.2.3 Conclusion

Despite its long list of potential or intended advantages, the deterministic approach of the Verification Method does not yet offer a high enough level of safety in all aspects of fire safety and a low enough level of over-design to be considered a valid design tool. The Verification Method offers similar advantages to the prescriptive codes such as the fast application process and the lack of uncertainty of complying with the performance criteria. However, when life safety of humans is the main concern, an adequate level of safety in the building must be prioritized over time efficiency and accessibility in the design phase.

Generally, the Verification Method is too generic and lacks guidance in essential aspects of the performing of a life safety analysis such as fire model selection and treatment of model input and output. In order to improve the validity of Verification Method, a more representative selection of design fires and occupant characteristics must be developed. Also, if the VM aims at being more accessible for designers who do not necessarily possess the knowledge of an experienced fire engineer, it is crucial that comprehensive guidance on fire modeling is provided. Such guidance must include fire model selection, handling of model input and treatment of model output. This guidance may also require interchangeable performance criteria, as the criteria depend on the selected fire model.

Even though the described issues were to be addressed in another version of the Verification Method, the main problem is still that the VM acts as a design method rather than a tool to verify compliance. The method replaces the designer by quantifying the building code's performance requirements, thereby interfering with the design process. This isn't the intent of the Verification Method, which is instead presented as a way to demonstrate compliance with the performance requirements set out in the building code. Unless the Verification Method returns to its original intentions, it cannot be considered a valid design tool.

6.3 Future Work

This study has provided insight into the desired advantages and observed weaknesses of the Verification Method as a design tool. These were identified based on examples from a case study, which highlighted issues that were specific for the selected building. Extending the study to include other examples than just a high-rise office building would help uncover other relevant issues of the method. These examples could include a warehouse containing high hazard combustibles and tall storage racks, or a retirement home housing occupants that are notably impaired in one or more ways.

Furthermore, an aspect of the design process that has not been looked into in this study is the economic impact of the solution selection. Although perhaps not as critical to the fire science community as focusing on performance criteria, there is a need to understand what benefits are provided at what cost as this is relevant to regulators, clients and regulatory developers [23]. Examining the economic advantages and weaknesses of the Verification Method might offer a different perspective on the method as a design tool.

A Appendix A Time Equivalence Calculation

A.1 Calculations

A Time Equivalence Formula is used when computing the fire severity of the structural members in the building. The formula applied for the design of this building is the one that was published by the CIB W14 group, derived by Pettersson (1973) based on ventilation parameters of the given compartment and the fuel load [18]. Time equivalence formulae are empirical, and it is a very crude and approximate method for introducing real fire behavior into fire engineering calculations. However, it is generally accepted to apply time equivalent formulae to protected steelwork and reinforced concrete members. The equivalent time of exposure will be calculated for the two retail stores.

The equivalent time of exposure in minutes is given by:

$$t_e = k_c w \, e_f \tag{A.1}$$

Where:

- e_f is the fuel load in MJ/m^2
- k_c is a parameter that accounts for different compartment linings
- w is the ventilation factor ($m^{-0.25}$)

The ventilation factor w is given by:

$$w = \frac{A_f}{\sqrt{A_v A_t \sqrt{H_v}}} \tag{A.2}$$

Where:

- A_f is the floor area of the compartment in [m^2]
- A_v is the total area of openings in the walls in [m^2]

- A_t is the total area of the internal bounding surfaces of the compartment in [m^2]
- H_v is the height of the windows in [m]

A.1.1 Fuel Load & k_c Parameter

The fuel load depends on the type of occupancy and what it contains, and the 95%-fractile fuel load was defined according to the *International Fire Engineering Guidelines* (IFEG) [21] as the following:

- Retail spaces: 1300 MJ/m^2
- Office spaces: 760 MJ/m^2
- Libraries: 2750 MJ/m^2

The IFEG does not define the fuel load for car parks, but it has been set to 260 MJ/m^2 [34]. The first floor of the building consists of half library space, half office space. Therefore a weighted fuel load has been created for the first floor: (2750+760)/2 = 1755 MJ/m^2.

The k_c term depends on the compartment lining materials. The value for k_c is equal to 0.07, which is the recommended value for compartments constructed of normal or lightweight concrete [18].

A.1.2 Ventilation factor

As the percentage of windows that will break cannot be known, a sensitivity analysis must be performed, examining different breakage percentages.

Because the car park does not have any window openings, but only a permanent opening for the cars to exit and enter through, 100 % "breakage" will be assumed only for the car park.

Table A-1: Compartment geometry:

Item	Small Store	Large Store	Car Park	Library /Office	Office
Floor Area (A_f)	170 m^2	323 m^2	750 m^2	620 m^2	620 m^2
Height	3 m	3 m	2.5 m	2.7 m	2.7 m
Internal bounding surface area (A_t)	522 m^2	881 m^2	176 m^2	380 m^2	270 m^2

Table A-2: Compartment openings:

Item	Small Store	Large Store	Car Park	Library /Office	Office
Total area of openings (A_v)	24 m^2	45 m^2	18 m^2	270 m^2	270 m^2
Height of windows (H_v)	3 m	3 m	2.5 m	2.7 m	2.7 m

Table A-3: Ventilation factors:

Case	Small Store	Large Store	Car Park	Library /Office	Office
All windows break	1.154	1.229	10.594	1.791	1.791
66 % of windows break	1.421	1.513	13.040	2.205	2.205
33 % of windows break	2.009	2.139	18.442	3.118	3.118

A.1.3 Time Equivalence

Table A-4: Time equivalence in minutes:

Case	Small Store	Large Store	Car Park	Library /Office	Office
All windows break	105	112	193	220	95
66 % of windows break	129	138	-	271	117
33 % of windows break	183	195	-	383	166

A.2 Discussion

The smaller the ventilation factor (area of openings), the higher the time equivalence. If the fire is vented, it will burn for a longer time at a lower rate of heat release than a fire that is not vented. Slow heating causes increased thermal exposure which can damage the structural elements significantly.

The reason for the high time equivalences shall be found in the assumptions for the method. The time equivalence formula derived by Petterson (1976) is based on the maximum temperature concept, which is sketched on Figure A-1 below. The idea is to define the equivalent fire severity as the time of exposure to the standard fire that would result in the same maximum temperature in a protected steel member as there would occur in the same steel member in a complete burnout of the fire compartment [18].

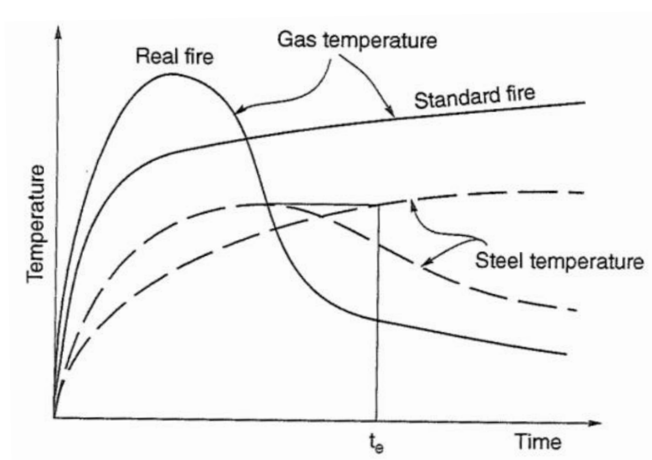


Figure A-1: Maximum temperature concept (Reproduced from Structural Design for Fire safety [18]).

The time equivalence of a structural component depends on the characteristics of the time-temperature curves for real fire exposure that Petterson's formula is based on. A generalized method of calculation of the time-temperature design curves have been developed by Maghnusson and Thelandersson (1970), who derived the method from heat balance calculations, using Kawagoe's (1958) equation for the burning rate of ventilation controlled fires [65]. These curves are often referred to as the *Swedish curves*. The curves have been developed in such a way that a high fuel load and a small ventilation opening will lead to higher gas temperatures in the compartment and extended decay periods, while a low fuel load and a large ventilation opening will have the opposite effect.

An important aspect of these time-temperature curves is the description of the cooling phase, i.e. the decaying stage of the real fire curve. The effect of various cooling phase values is shown in Figure A-2 [66].

As Figure A-2 shows, the rate of temperature decrease has a significant impact on the maximum temperature of the steel member and the length of its decaying phase. The Swedish curves have been developed theoretically and compared to a number of full scale tests. However, several experimental studies have measured the gas temperatures in post-flashover fires, and there is considerable scatter between the results of the different studies on the matter [18]. Traditionally, spatially homogeneous temperature conditions are assumed for quantifying and modeling compartment fires, but a study by J. Stern-Gottfried (2010) unveiled the lack of this uniformity, which then questions the validity of the assumption of uniform temperature conditions [67]. Also, when the Swedish curves were developed in 1970, the calculation of the temperature-time curve for the combustion gases during the cooling phase had only been studied sparsely [66]. These circumstances may result in an arbitrary description of the real fire time evolution, including its cooling phase, resulting in misleading temperatures of the steel component.

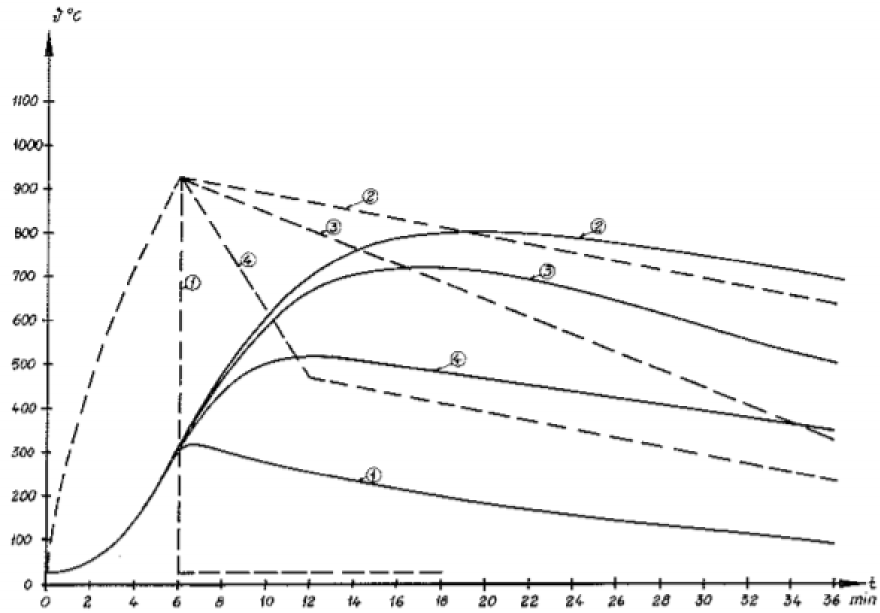


Fig. 3. Variation in the temperature, ϑ_s, of a steel column with the time, t, calculated on the basis of temperature-time curves, which differ in shape during the cooling phase (dash-line curves).

F_s/V_s = Ratio, in m^{-1}, of the fire-exposed surface area, i.e. the total bounding surface area, of the column to the steel volume of the column.

ε_r = Resultant emissivity.

———— ϑ_s

– – – – – ϑ_g at $A\sqrt{H}/A_t = 0.08\ m^{1/2}$.

q = 12 Mcal · m².

1. Instantaneous cooling. Rate of decrease in temperature ∞ °C · h^{-1}.
2. Linear rate of decrease in temperature, 600°C · h^{-1}.
3. Linear rate of decrease in temperature, 1200°C · h^{-1}.
4. Linear rate of decrease in temperature, 6 min $\leq t \leq$ 12 min, 4600°C · h^{-1}; $t \geq 12$ min, 600°C · h^{-1}.

F_s/V_s = 100 m^{-1} $\varepsilon_r = 0.5$.

Figure A-2: Effect of cooling phase (Reproduced from S. E. Magnusson & S. Thelandersson's work [66]).

Additionally, the full scale experiments that the Swedish curves were based on were most likely affected by radiation errors. Research by S. Welch et al. (2007) [68] analyzes how the thermal couples used in most full scale experiments are affected by radiation from hot gases and structures so that they measure a temperature that is not a gas temperature, but a combination of the gas temperature and radiation coming from the walls, thus they appear too high compared to the actual gas temperature in the compartment. This is particularly the case in the lower layer of the compartment (during the fire) and in ambient inflow regions, where the gas temperature becomes largely overestimated due to radiation errors.

Examples of full scale tests that were executed in the 1960s and 1970s are found in *The temperature attained by steel in building fires* by E.G. Butcher (1966) [69] and in *Brandversuche Lehrte* (1976) [70] ("Fire tests in Lehrte"). In these experiments, the thermocouples had been distributed somewhat evenly throughout the compartments, meaning that they were placed close to the ceiling, floor or closer to the center of the compartment. In the Brandversuche Lehrte experiments, some thermocouples were also placed right by inflow regions by the wall. Those thermocouples and the ones placed closer to the floor would, according to Welch's research, indicate a gas temperature higher than the actual one, resulting in a higher mean gas temperature for the compartment.

A different study, *The Error in Gas Temperature Measurements with Thermocouples* (2012) [71] further unravels the effect of radiation errors. The authors illustrate the correlation between the error of measure and the diameter/length of the thermocouple utilized in the experiment. Their results indicate that a thermocouple of diameter 2.0 mm would cause a larger error than a thermocouple of diameter 0.1 mm. In the Brandversuche Lehrte experiments, thermocouples of 3.0 mm were used to measure gas temperatures. According to the 2012 study, thermocouples of this size would result in relatively high measurement errors.

All in all, due to the time evolution of the design fire curves, the manner in which they have been developed and their inclusion of radiation errors, the maximum temperature of the gas in the compartment during the cooling phase will be estimated as very high, particularly when the fuel load is high and the ventilation area is small. This is the case as the walls within the compartment will have heated significantly due to the high fuel load, causing the radiation from the walls to the thermocouples to be much more significant. If the thermocouple didn't include radiation errors and only measured the actual gas temperature, then the measured temperature would be much lower after the fire stops burning. However, radiation errors are included, causing the cooling phase to be much slower as the thermocouples measure the radiation from the linings rather than the gas temperature. The design fire curves that Petterson's time equivalence formula is based on therefore include both gas and solid temperatures, but the time equivalence model transfers heat as if it was the gas temperature only. The energy in the model is thus being over-dimensioned, leading to the time equivalence being over-dimensioned as well.

A.2.1 Significance for the Verification Method Approach

The Verification Method encourages the application of a time equivalence formula taken from Eurocode 1. As discussed above, time equivalence formulas will lead to high fire resistance ratings being required, possibly higher than the available ratings offer. In order to lower the time equivalence, either the ventilation area must be increased or the fuel load must be decreased. The ventilation area can be augmented by presupposing a higher breakage percentage, while the fuel load can be reduced by applying reduction factors.

The possible reduction factors for the fuel load are listed in the VM. The fuel load can be reduced by making the compartment equipped with sprinklers, automatic fire detection systems, providing safe access routes for firefighting etc. The validity of the reduction factors are questioned as the actual fuel load in the building logically won't be reduced by e.g. adding automatic fire detection systems. Thereby the uncertainty of the final calculated time equivalence is enhanced. Increasing the ventilation area is also considered an uncertain approach, as it cannot be known exactly how much the breakage percentage will be.

Appendix B Comparison Study

B.1 Introduction

A comparative study between two common fire models, a zone model and a computational fluid dynamics (CFD) model is presented in this document. The study is revolved around the fire scenario proposed for the retail space on the ground floor in the high-rise building. The zone-model corresponds to the Consolidated Model of Fire and Smoke Transport (CFAST ver 7.2.1), and the CFD model corresponds for Fire Dynamics Simulator (FDS v. 6.5.3). The intention of this document is to highlight the differences in results, complexity of use and selection of input parameters and output values for the purposes of design.

The outcomes of the simulations that are assessed in the document are related to the tenability criteria proposed in the Performance-Based Design method. The tenability criteria are based on height of the hot smoke layer and thermal criteria in the shape of temperatures of the upper and lower layer. The temperature of the upper layer is based on a limit of the radiation from the hot layer, which is tolerable to humans.

B.1.1 Assumptions and limitations

The assumptions for the models built in this exercise are:

- Definition of control volumes (CFAST) and cell size (FDS);
- Evolution of the area of the fire;
- Evolution of the heat release rate (CFAST) and heat release rate per unit area (FDS);
- Chemical reaction and heat of combustion;
- Heat transfer to solid boundaries.

B.1.1.1 Determination of smoke layer height

Zone models determine the hot layer height as a distinctive interface between the hot upper layer and the colder lower layer, which in reality isn't the case as this region is not a distinct line. Therefore, the quantity of the smoke layer height is computed directly in CFAST, while in FDS, there are not two distinct zones as the temperature profile is continuous. There are various ways to estimate a smoke layer height, such as the N%-method or the Integral Ratio Method [72]. The FDS program itself does contain a method to calculate the smoke layer height for given spot locations in the XY-plane in the FDS model.

The method that the FDS program utilizes is based on a continuous function of T(z) defining the temperature as a function of the height z above the floor, where z = 0 is the floor, and z = H is the ceiling height [50]. Additionally, T_u is defined as the upper layer temperature, T_l as the lower layer temperature and z_{int} as the interface height. Then the following quantities can be computed:

$$\left(H - z_{int}\right) T_u + z_{int} T_l = \int_0^H T(z)\, dz = I_1 \qquad \text{(B.1)}$$

$$\left(H - z_{int}\right) \frac{1}{T_u} + z_{int} \frac{1}{T_l} = \int_0^H \frac{1}{T(z)}\, dz = I_2 \qquad \text{(B.2)}$$

The quantities are solved for z_{int}, and the average temperatures are defined as:

$$\left(H - z_{int}\right) T_u = \int_{z_{int}}^H T(z)\, dz \qquad \text{(B.3)}$$

$$z_{int} T_l = \int_0^{z_{int}} T(z)\, dz \qquad \text{(B.4)}$$

In order to find a mean layer height, upper and lower temperature for the FDS model, several layer zoning devices will be placed in the model, distributed evenly throughout the space. However, when the interface height is determined using the aforementioned method, there's a high possibility that the interface height will differ significantly from CFAST's results. In order to compare the simulation outcomes properly, the temperature profiles of FDS will be compared to the ones of CFAST. The temperature profiles in FDS will be created with thermocouple trees distributed evenly on a line in the FDS model, and also via trees of planes measuring the mean temperature in a given zone that is equal to a control volume in the CFAST model. Emmon's method of measuring the maximum slopes of the temperature profile and determining the layer height as the midway point of the two greatest slopes [73] will be applied to the temperature profiles.

B.1.1.2 Determination of temperature

Comparing the temperatures of the two models generates the same issues as with the determination of smoke layer height. The temperatures in CFAST are lumped values, while they are spatially distributed values in FDS. The same algorithm that allows for layer height determination in FDS also measures the temperature of the upper and lower layer, but these are likely to differ from the CFAST values. Therefore the temperature values from CFAST will also be compared to temperature profiles from FDS.

B.2 Model design in CFAST

B.2.1 Input parameters

B.2.1.1 Geometry and control volumes

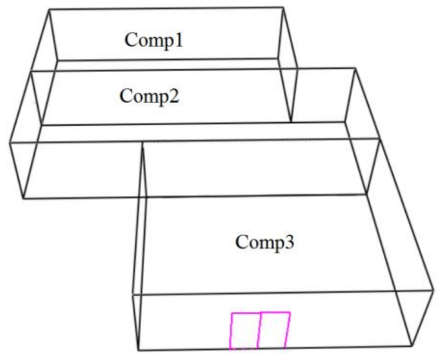


Figure B-1: Geometry of CFAST model.

The CFAST model for the small shop on the ground floor is visualized on Figure B-1. It consists of three compartments, compartment 1, 2 and 3, which are all interconnected through vertical openings in CFAST. All compartments are 3.0 m tall. The individual geometries of the compartments are listed in Table B-1.

Compartment	Width [m]	Depth [m]	Floor area [m^2]
1	11.5	5.3	61.0
2	14	4.7	65.8
3	9	7.0	63.0

Table B-1: Geometry of compartments in CFAST model.

The overall width and depth of the model are 14 x 17 m, and the total floor area is 190 m^2. The roof of the model is flat. One double-door is assumed open in the model as it can be comprehended from Figure B-1. This opening has a width of 1.8 m and a height of 2.0 m, and is open throughout the simulation.

The walls, floors and ceilings of the compartments are assigned to have characteristics equal to concrete. The characteristics are listed in Table B-2.

Concrete characteristic	Value
Specific heat	1.04 kJ/kg-K
Conductivity	1.8 W/m-K
Density	2280 kG/m^3

Table B-2: Material characteristics for compartment walls, ceilings and floors in CFAST.

B.2.1.2 Combustion model

The combustion model has been determined based on a sensitivity analysis between various fuels. The assumed fuel is therefore polystyrene (C_8H_8):

$$C_8H_8 + v_{O_2}O_2 + v_{N_2}N_2 \quad \rightarrow \quad v_{CO_2}CO_2 + v_{H_2O}H_2O + v_{CO}CO + v_{soot}Soot + v_{N_2}N_2$$

Heat of combustion: 39,700 kJ/kg

CO-yield: 0.06 g/g

Soot yield: 0.166 g/g

Radiative fraction: 0.35

B.2.1.3 Fire model

- The evolution of the heat release rate is assumed to follow a t^2 growth with a fire growth rate of 0.101 kW/s^2 until the peak HRR of 2700 kW is reached after 164 sec. The time evolution of HRR is plotted on Figure B-2.

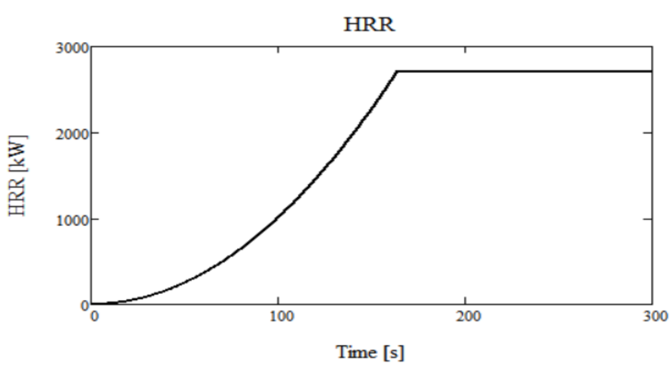


Figure B-2: HRR evolution in CFAST model.

- The fire area is assumed to peak at the same time as the HRR peaks, and the peak area is assumed conservatively to 5.0 m^2. The values for the area are directly inserted to the CFAST input, meaning that a spread rate is not required. However, the equivalent spread rate would be equal to 7.7 mm/s. The time evolution of fire area is shown in Figure B-3.

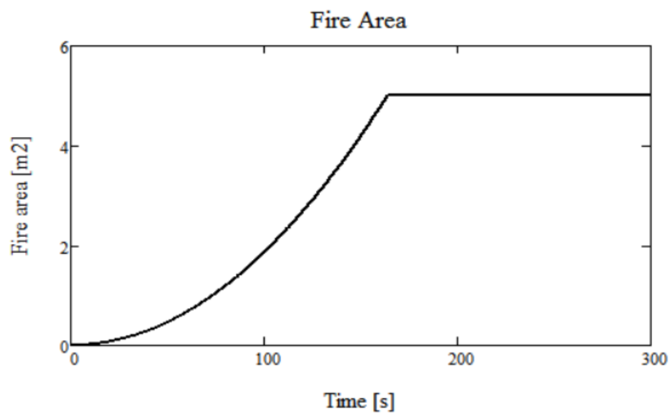


Figure B-3: Fire area evolution in CFAST model.

- The fire is located 0.5 m above the ground in the center of compartment 2.

B.2.2 Outcomes

CFAST provides average values for the upper and lower layer of each of the control volumes. The parameters that are focused on in this comparison are noted below:

- The height of the upper layer (smoke layer height);
- The temperature of the upper layer;
- The temperature of the lower layer.

B.2.3 Results

B.2.3.1 Smoke evolution

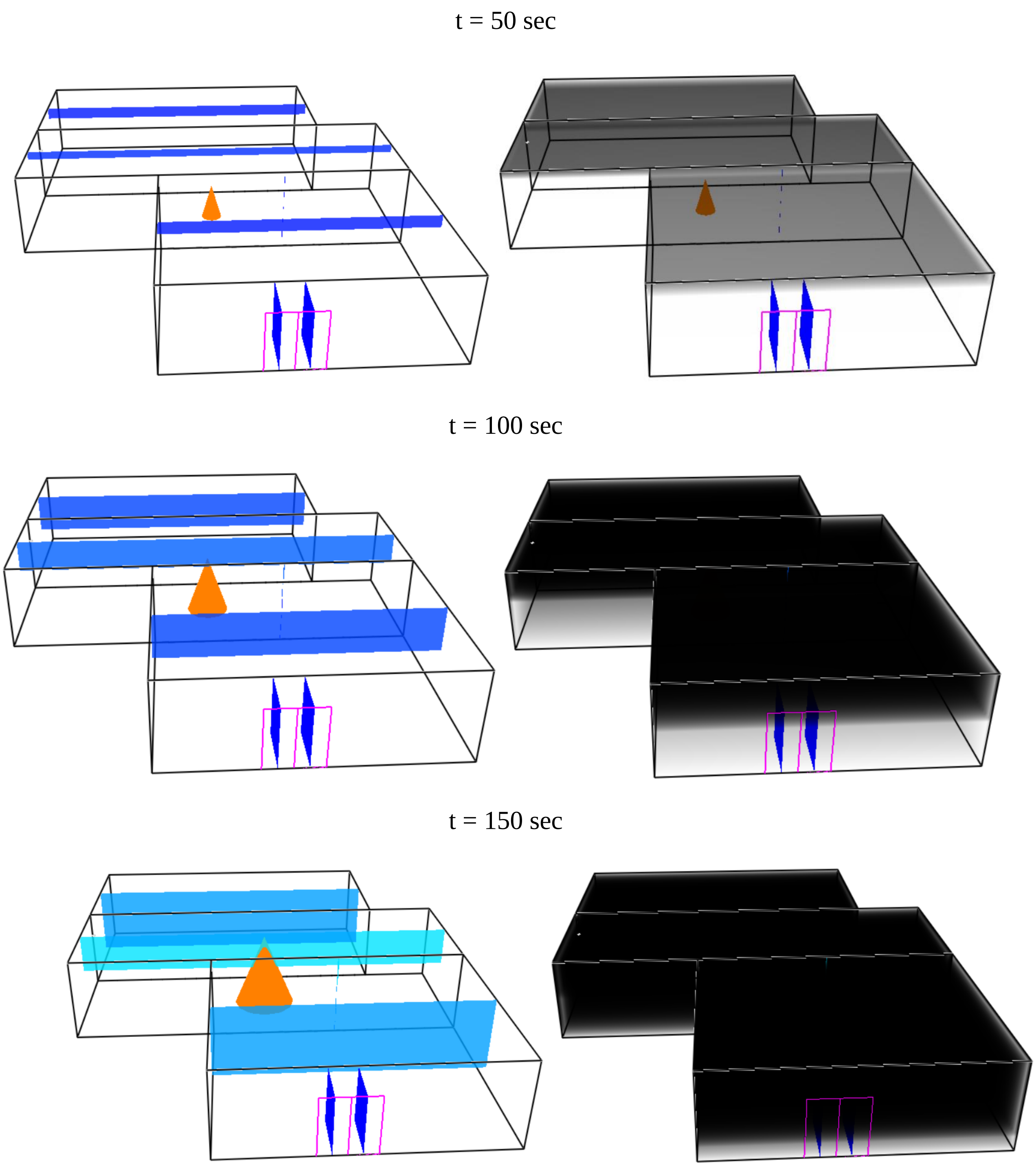


Figure B-4: Evolution of smoke layer at specified times. Left: Upper layer temperature. Right: Smoke visualization

B.2.3.2 Smoke layer height

The time evolution of the smoke layer height in each of the control volumes is visualized on Figure B-5 including a line indicating the exceeding of the performance criterion of 2.2 m.

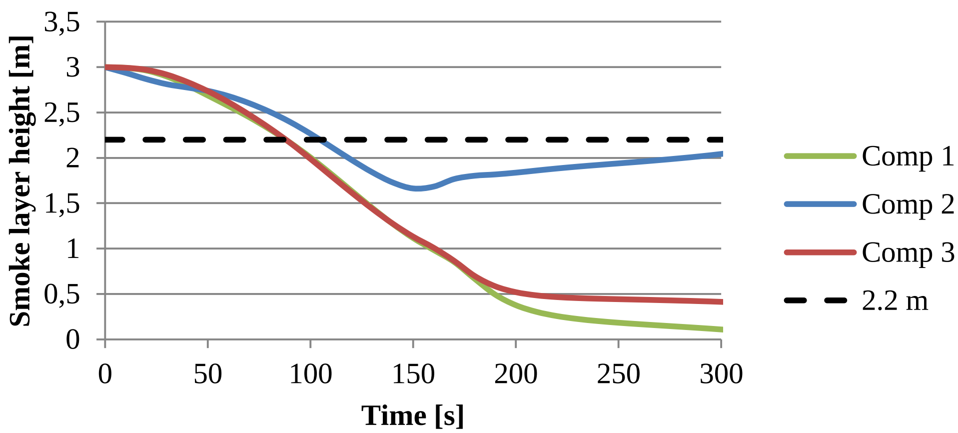


Figure B-5: Evolution of smoke layer height for each control volume in CFAST.

The time to reach a height of 2.2 m above the floor is shown in Table B-3 for each of the control volumes. The table shows that the time for the smoke layer to reach z = 2.2 m is faster in the control volumes that do not contain the fire.

Area	Smoke layer height [s]
Comp 1	88
Comp 2	105
Comp 3	88

Table B-3: Time for the smoke layer to reach z = 2.2 m in each control volume.

B.2.3.3 Lower and upper layer temperature

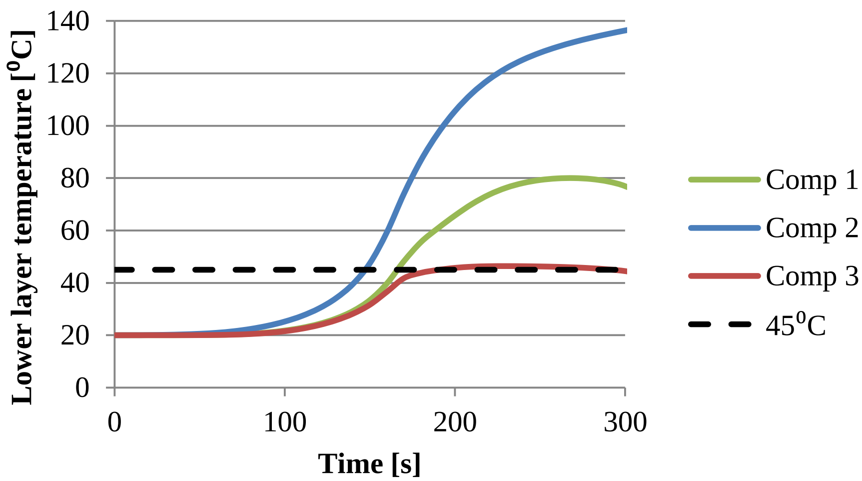


Figure B-6: Evolution of lower layer temperature for each control volume.

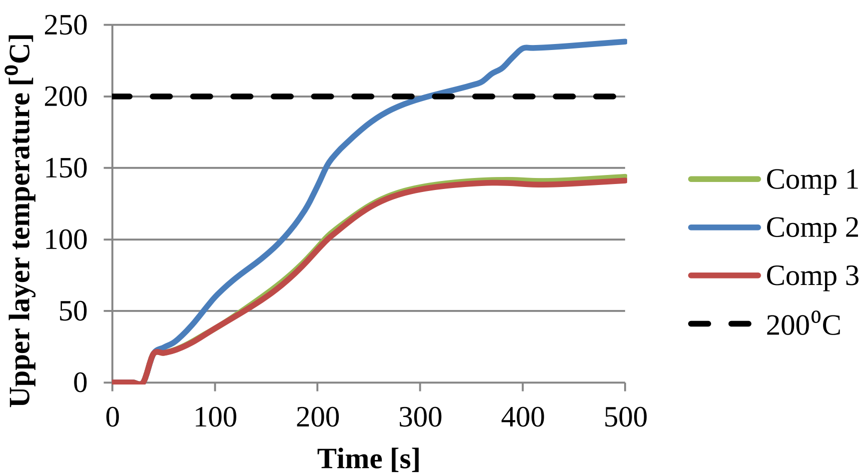


Figure B-7: Evolution of upper layer temperature for each control volume.

Figure B-6 and Figure B-7 show the time evolution of the temperature of the lower and upper layer in each of the control volumes. The times that it take for the performance criteria (45^{o}C for the lower layer and 200^{o}C for the upper layer) to be exceeded are shown in Table B-4. As it would be expected for the temperature criteria, the critical control volume is the one that contains the fire (compartment 2).

Area	Lower layer temperature [s]	Upper layer temperature [s]
Comp 1	166	> 500
Comp 2	147	270
Comp 3	191	> 500

Table B-4: Times to reach 45ºC for the lower layer and 200ºC for the upper layer for each control volume

B.2.4 Summary

Table B-5 provides a summary of the results for the Available Safe Egress Time (ASET) using CFAST for the small shop on the ground floor based on the performance criteria for the smoke layer height and the temperature of the lower and upper layer. It is clearly shown that the conservative tenability criterion is the smoke layer height.

Area	Smoke layer height [s]	Lower layer temp. [s]	Upper layer temp. [s]
Comp 1	88	166	> 500
Comp 2	105	147	270
Comp 3	88	191	> 500

Table B-5: ASET corresponding to different tenability criteria obtained with CFAST

B.3 Model design in FDS

B.3.1 Input parameters

B.3.1.1 Geometry

- The overall dimensions of the FDS-model: Width = 14 m, depth = 17 m, height = 3 m.
- The obstruction acting as the space reserved for the car park entry ramp is 4.5 m x 6.5 m x 3 m.
- The obstruction acting as the space reserved for the elevator is 2.5 m x 5.3 m x 3 m.

- One double door that has a width of 2 m and a height of 2 m is considered open.
- Mesh limits are separated from building openings by a space of 1.8 m on the front side that contains the door, and 0.8 m on the left side of the building without any doors.
- The Mesh boundaries on the front and the left sides are connected to OPEN vents, while the vents on the top, bottom, rear and right sides have been defined as concrete.
- Solid boundaries of the building and the obstructions within it are set to concrete with the material characteristics shown in Table B-6.

Concrete characteristic	Value
Specific heat	1.04 kJ/kg-K
Conductivity	1.8 W/m-K
Density	2280 kG/m^3

Table B-6: Material characteristics for compartment walls, ceilings and floors in FDS.

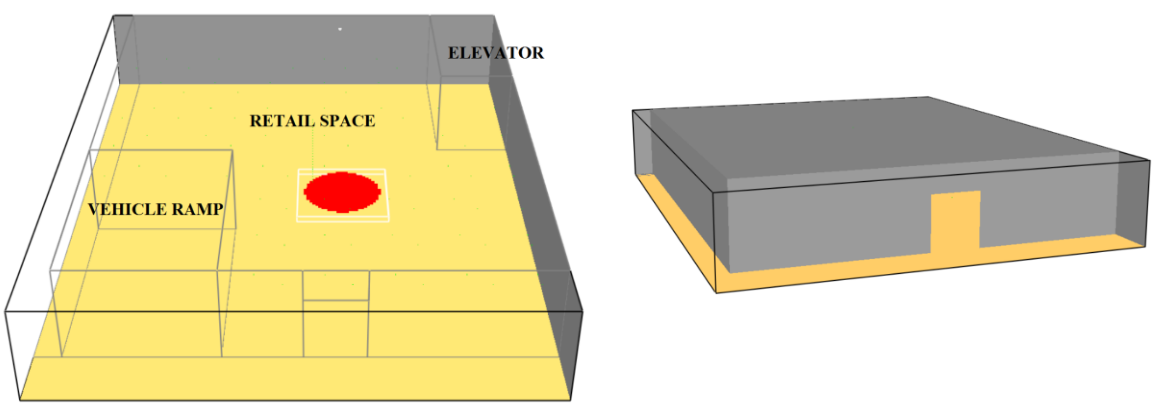


Figure B-8: Screenshots of FDS model.

B.3.1.2 Combustion model

The combustion model has been determined based on a sensitivity analysis between various fuels. The assumed fuel type is therefore polystyrene (C_8H_8):

$$C_8H_8 + v_{O_2}O_2 + v_{N_2}N_2 \quad \rightarrow \quad v_{CO_2}CO_2 + v_{H_2O}H_2O + v_{CO}CO + v_{soot}Soot + v_{N_2}N_2$$

Heat of combustion: 39,700 kJ/kg

CO-yield: 0.06 g/g

Soot yield: 0.166 g/g

Radiative fraction: 0.35

B.3.1.3 Mesh

Grid size of entire model: 0.10 m x 0.10 m x 0.10 m (834,720 cells).

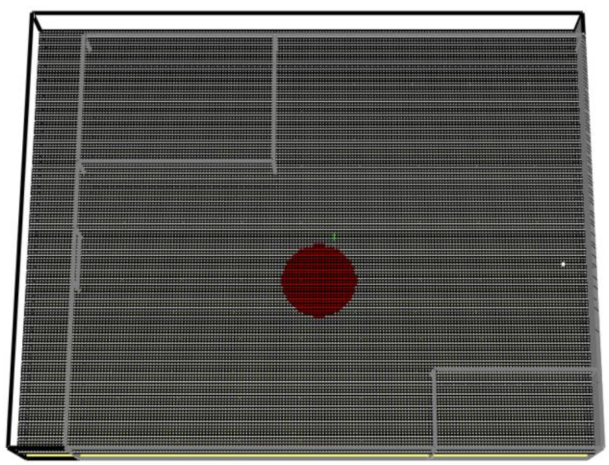
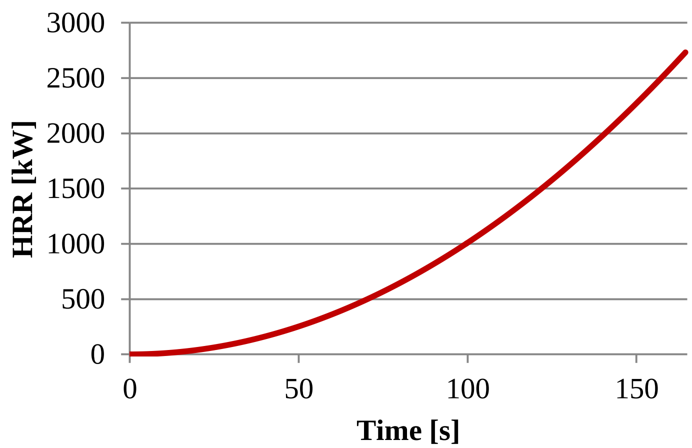


Figure B-9: Illustration of grid size in FDS.

B.3.1.4 Fire model

- Assumed Heat Release Rate per Unit Area (HRRPUA): 540 $kW \cdot m^2$ (Equal to the maximum peak HRR in the CFAST model of 2700 kW distributed on a 5 m^2 area).

- The fire is modeled as a vent on a polystyrene base. The vent is circular with HRRPUA as noted above and a spread rate (v_s) of 7.7 mm·s^{-1}. This will result in a fire area of 5 m^2 at the same time the peak HRR of 2700 kW is reached, i.e. after 164 s.
- The fire is located at a height of 0.5 m above the ground in the center of the retail space.
- The fire starts at the center of the circular vent and grows radially at the aforementioned spread rate.
- The HRR is equal to $0.101\frac{kW}{s^2}t^2$ and visualized in Figure B-10.



-

Figure B-10: HRR input for FDS

B.3.2 Outcomes

FDS provides spatially distributed values for the desired parameters. The parameters that are focused on in this comparison are noted below:

- The layer height measured by zoning layer devices;
- The temperature of the space, which is measured by zoning layer devices, thermocouple trees and mean temperatures of zones.

B.3.3 Results

B.3.3.1 Heat release rate

Figure B-11 shows the input and output HRR for the polystyrene fire modeled in FDS. The output HRR shows the same trend as the input HRR, however, with significant noise due to oxygen becoming less available in the region near the plume. The fire in the retail space is nonetheless still in a fuel-controlled regime as the output HRR follows the input HRR.

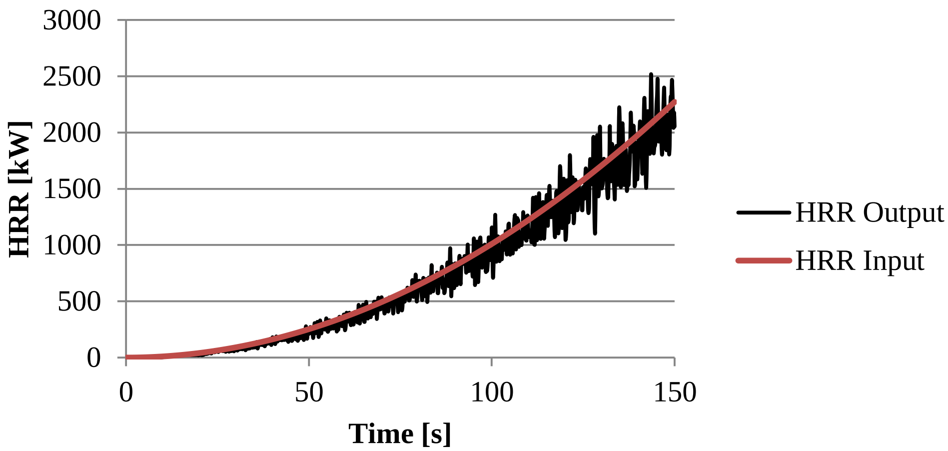


Figure B-11: Heat Release Rate input in FDS (red line) and output (black line).

B.3.3.2 Smoke evolution

The time evolution of the smoke in the retail space at different times visualized in Smokeview is shown on Figure B-12. The smoke spreads radially from the fire that is located centrally in the space, until it is more or less evenly distributed throughout the room. Once the smoke layer becomes deep enough, the smoke starts exiting out the door in the front of the shop.

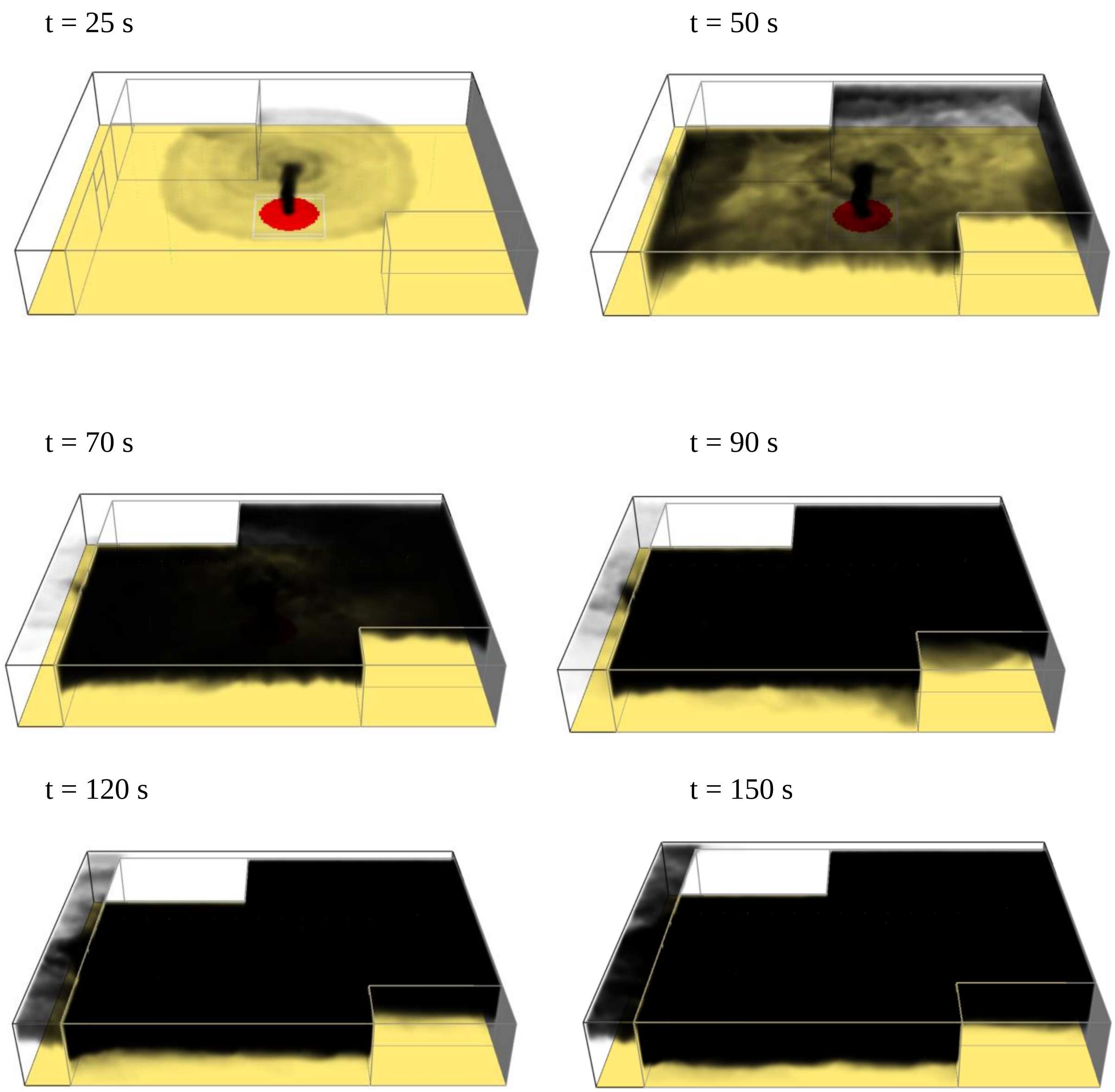


Figure B-12: Evolution of the smoke layer in the retail space for times 25, 50, 70, 90, 120 and 150 s.

B.3.3.3 Layer zoning devices

The layer zoning devices in FDS allow for an estimation of smoke layer height, upper temperature and lower temperature. 69 layer zoning devices have been uniformly distributed throughout the retail space. A mean of their estimated values have been compared with outcomes from the CFAST model. For the layer height, the rate at which it decreases in FDS is somewhat similar to the rate calculated by CFAST, however, they do intersect, meaning that at some times, CFAST provides a lower layer height, while at other times the FDS calculations yield a more conservative outcome. At the point when the tenability criterion is exceeded, FDS calculates the lowest ASET as 70 s.

While FDS clearly provides lower values of the lower temperature than CFAST, the upper temperatures appear to show the same trend, with CFAST proposing the conservative values.

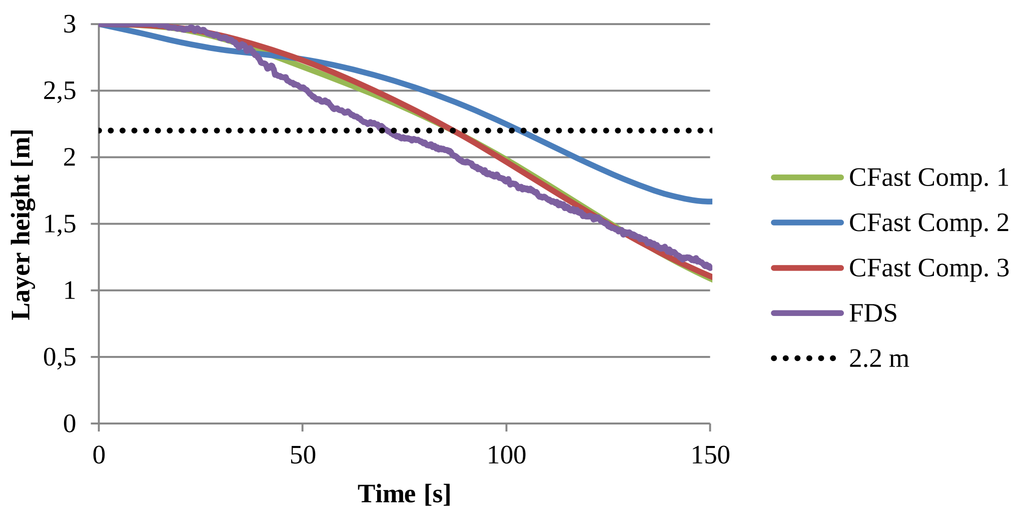


Figure B-13: Layer height evolution.

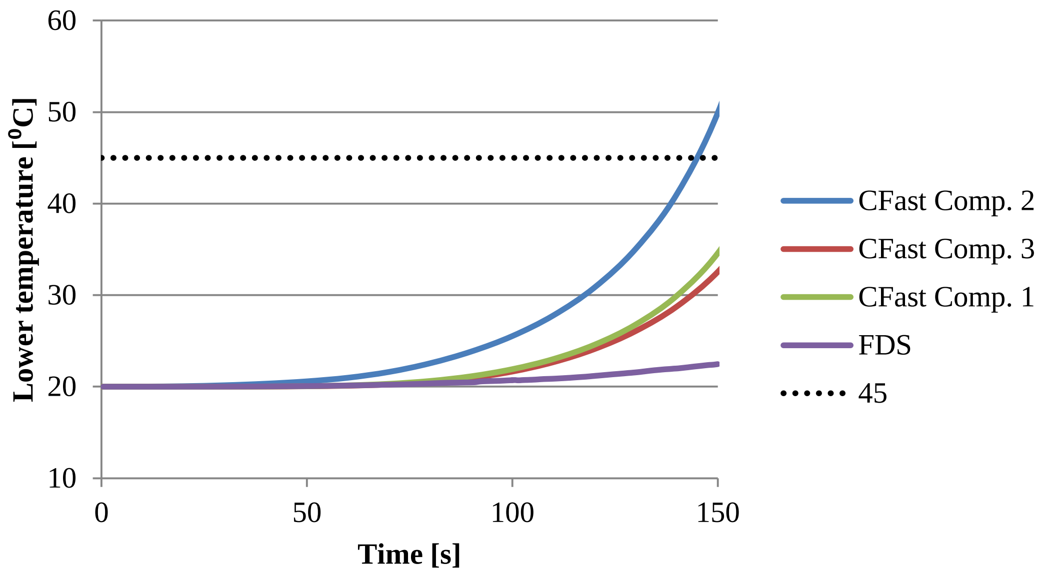


Figure B-14: Lower layer temperature evolution.

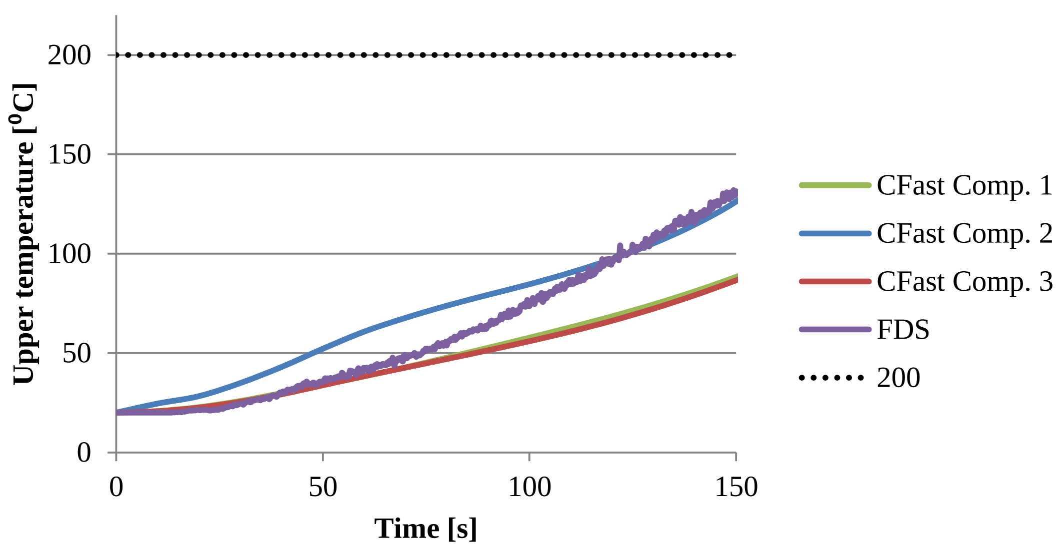


Figure B-15: Upper layer temperature evolution.

B.3.3.4 Temperature profiles

12 thermocouple trees have been located on a straight line in the middle of the x-axis in the retail space with 1 m spacing. The first 7 trees are therefore located within compartment 3, while the remaining 5 are placed within compartment 2. The zones measuring the mean temperatures in layers have been formed so that the zones fit the three CFAST compartments.

The plots in Figure B-16 show that the compartment (comp. 3) exhibiting the most severe tenability conditions, isn't characterized by a uniform layer of temperatures, while the temperature profiles in the fire compartment (comp. 2) pose more consistent results. This is especially apparent from plots c) and d).

Temperature profiles based on the mean temperature for each of the compartments have also been created in order to compare the expected layer heights. In order to characterize the layer height from Emmon's maximum slope method, a certain level of uniformity is required to prevent the predictive power of the method from decreasing. This is not the case of the FDS temperature profiles though, as the temperature above ambient tend to increase with the height, indicating no distinct layer. This will inevitably lead to extremely crude estimations of the layer height. Nonetheless, the CFAST values appear to lie in the middle part between the lower maximum gradient and the top of the ceiling, or further down.

The resulting mean layer height from the layer zoning devices have been inserted to the temperature profiles in Figure B-17, Figure B-18 and Figure B-19, along with the first standard deviation limits. From the plots, it becomes apparent that FDS and CFAST provide equally severe results for t = 30 s and t = 140 s, while at the time that the layer height criterion is exceeded in CFAST, more than 84% of the layer zoning devices will provide more critical layer heights than CFAST.

Concerning the temperatures, the data shows that the majority of the lower layer values do not exceed the ambient temperature before approaching the layer height. Measuring the lower layer temperature just beneath the layer height limit will provide more critical values. The upper layer temperature is difficult to determine, as all temperatures above the layer height limit vary strongly. Although FDS calculates the mean upper layer temperature to approximately 120°C as shown on Figure B-15, Figure B-19 indicates that the upper layer temperatures go all the way up to 250°C. It could therefore be argued that a higher upper layer temperature would be more appropriate.

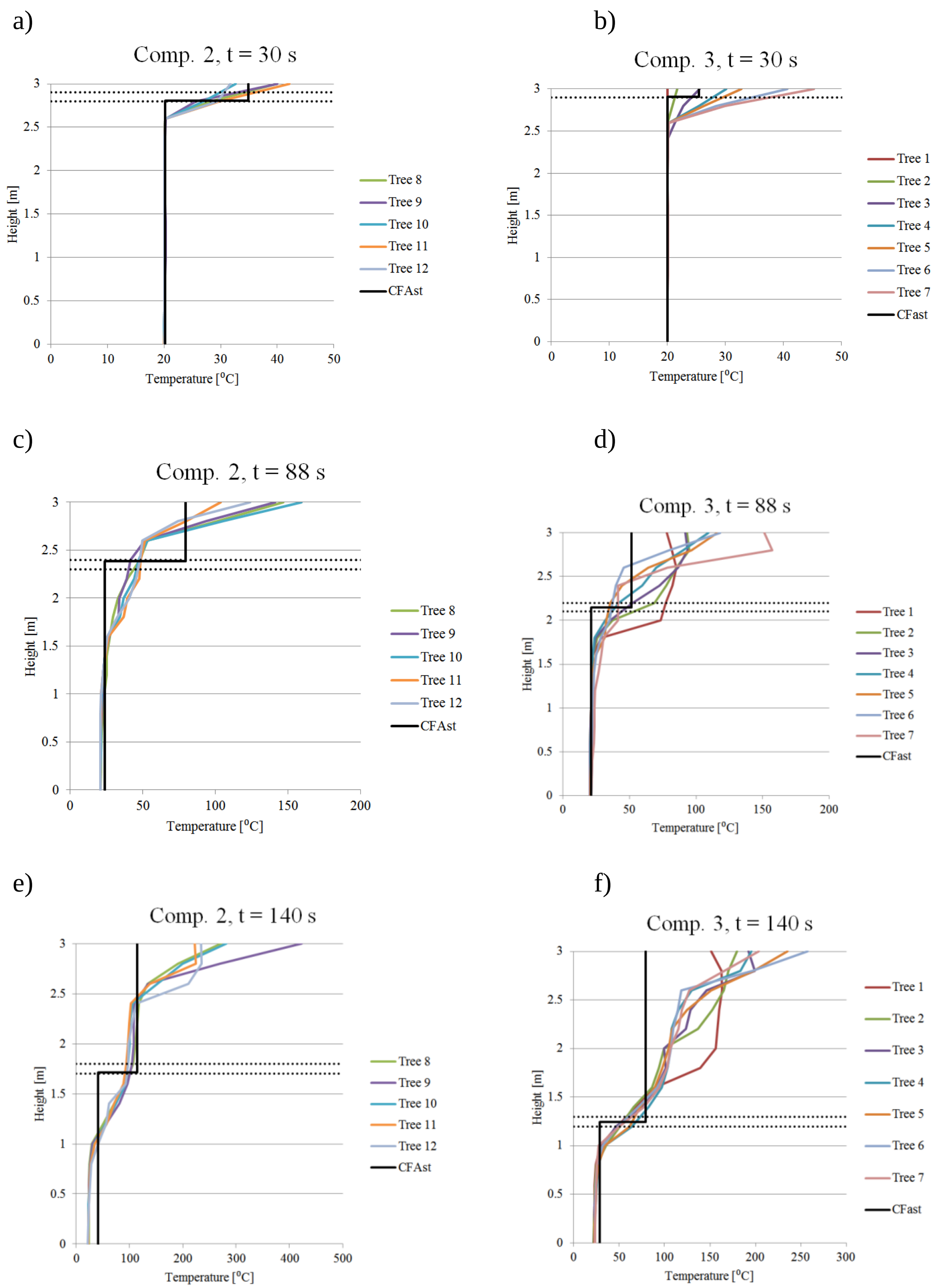


Figure B-16: Temperature profiles for compartment 2 and 3 calculated from thermo-couple trees. The black dashed lines indicate the size boundaries for the cell that the CFAST values lie within.

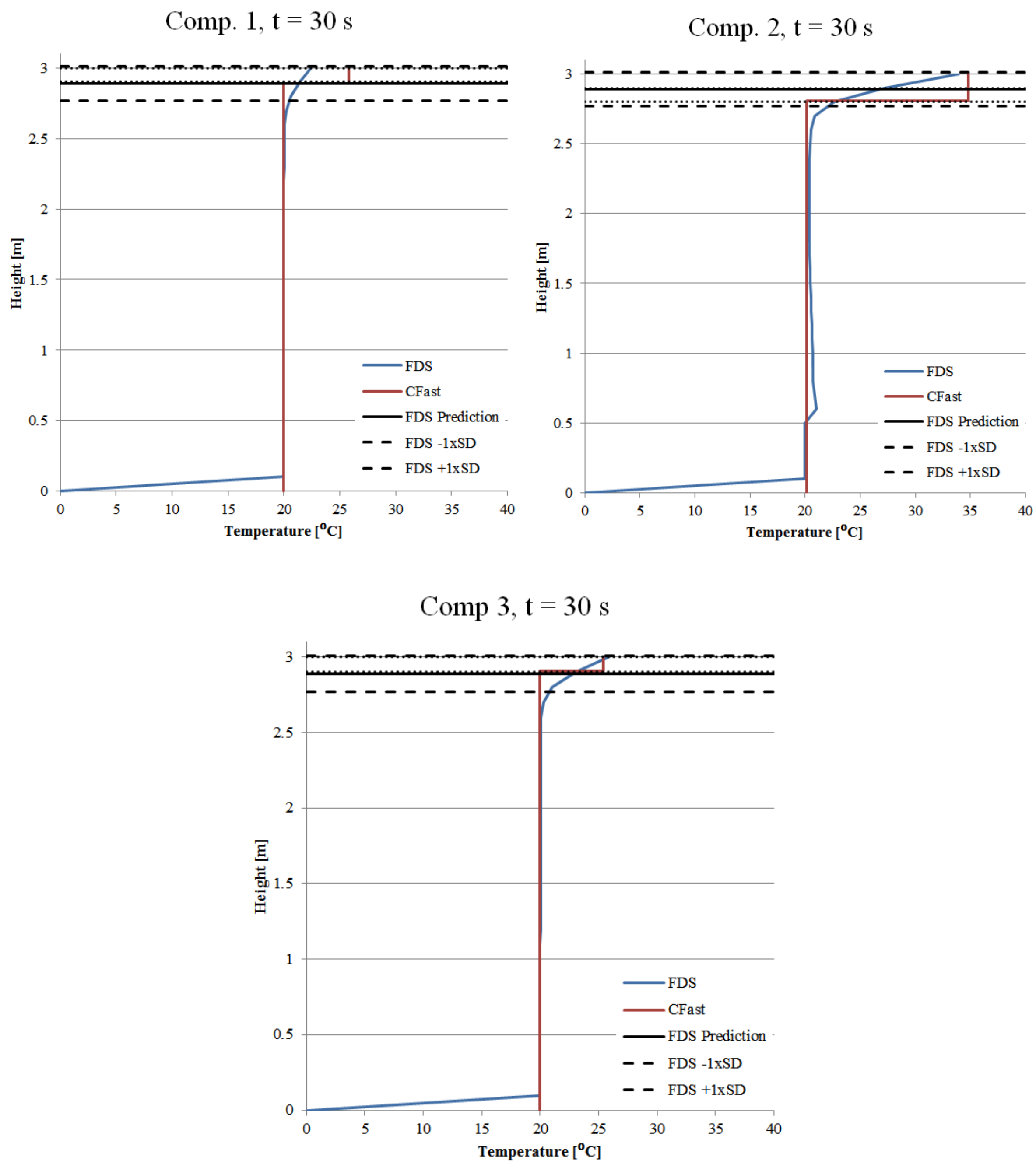


Figure B-17: Temperature profiles at t = 30 s. The short black dashed lines indicate the size boundaries for the cell that the CFAST values lie within, while the long dashed lines indicate the SD limits for the FDS values.

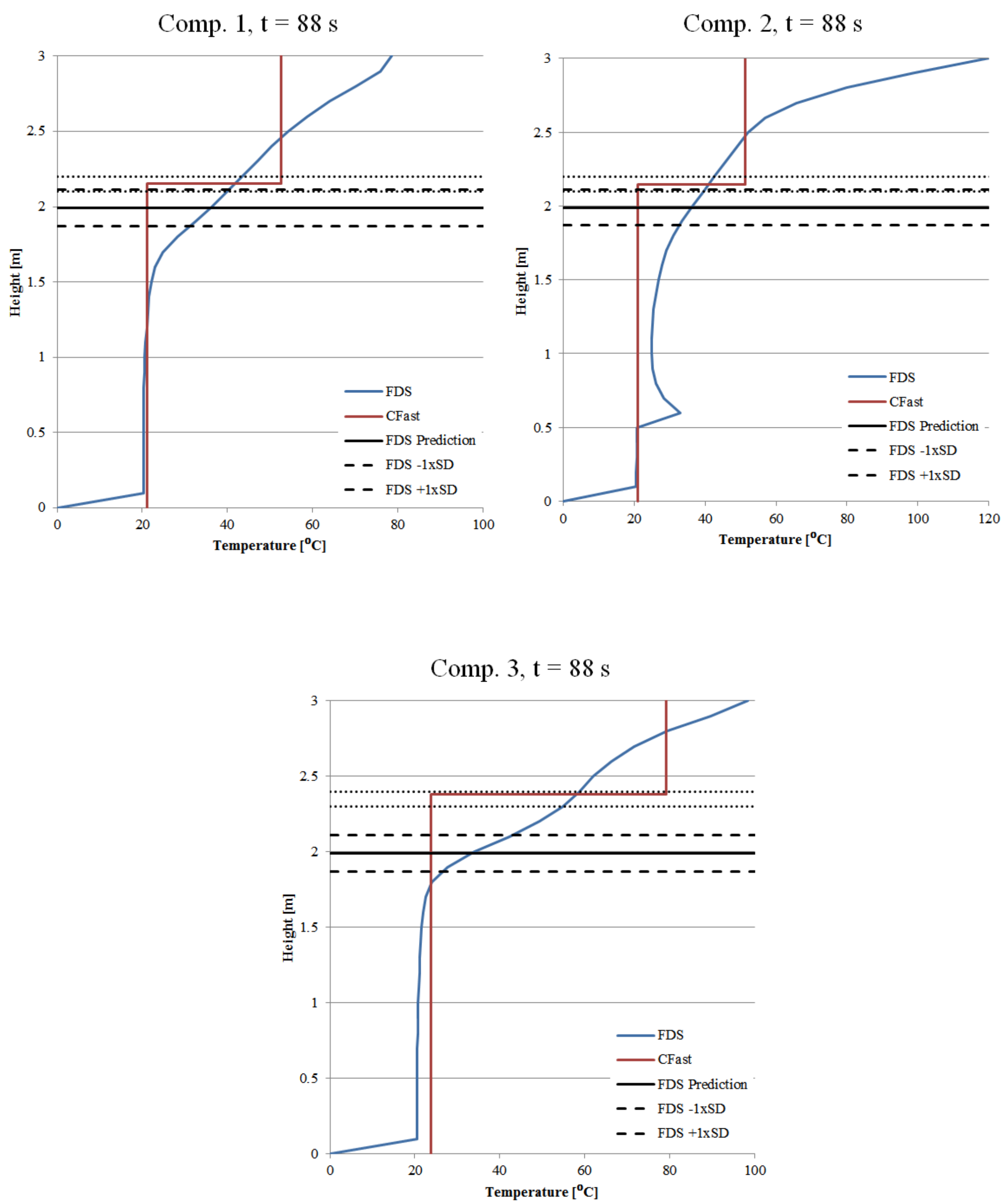


Figure B-18: Temperature profiles at t = 88 s. The short black dashed lines indicate the size boundaries for the cell that the CFAST values lie within, while the long dashed lines indicate the SD limits for the FDS values.

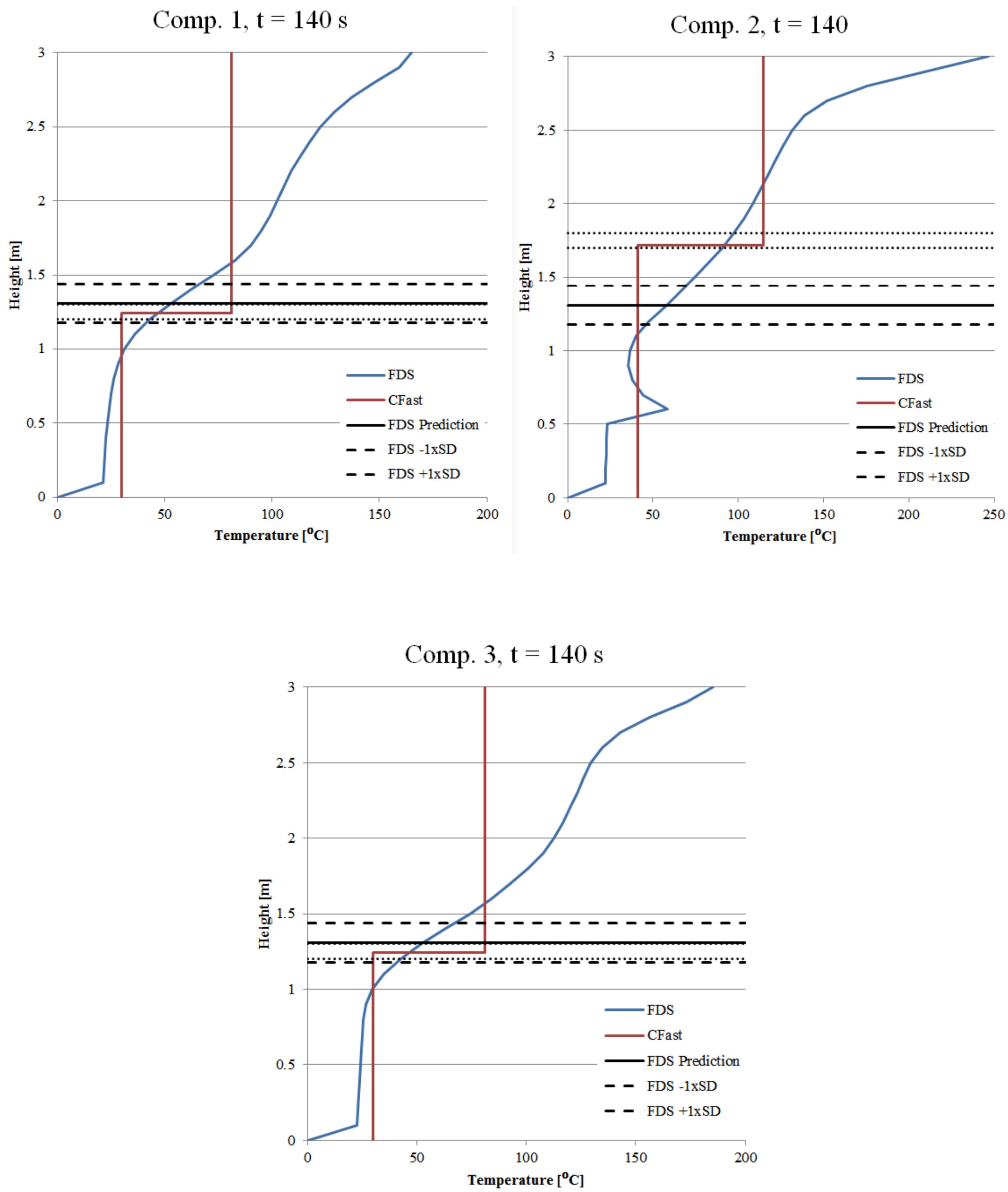


Figure B-19: Temperature profiles at t = 140 s. The short black dashed lines indicate the size boundaries for the cell that the CFAST values lie within, while the long dashed lines indicate the SD limits for the FDS values

B.3.4 Summary

Table B-7 provides a summary of approximate results for the Available Safe Egress Time (ASET) using mean values from zoning layer devices in FDS for the small shop on the ground floor based on the performance criteria for the smoke layer height and the temperature of the lower and upper layer. It is clearly shown that the conservative tenability criterion is the smoke layer height.

Area	Smoke layer height [s]	Lower layer temp. [s]	Upper layer temp. [s]
Retail area	70	>150	>150

Table B-7: ASET corresponding to different tenability criteria obtained with CFAST

B.4 Conclusions

The comparative study highlights a number of key points relevant to following the VM approach:

- The use of FDS and CFAST does not always provide comparable results when comparing average values of all relevant physical parameters (layer height, upper and lower layer temperatures).
- The tenability criteria that are used as a basis for the design need to be appropriate to the model being used in the analysis. The criteria that are appropriate for one type of model may not be suitable for other model types, which may then require expert input from the user. The three fundamental criteria examined in this study are appropriate for evaluation in CFAST, but cannot be used without expert input for CFD models that deliver spatial distribution. The Verification Method proposes no guidance on this matter.

- The inputs for the fire model will in many cases have a major effect on the output. The more sophisticated the model is, the more inputs are necessary to define and often they are complex to describe as well. A complex CFD model will also provide a wider range of outputs, which will also require more expert input when treating them. The Verification Method does not provide guide-lines on all necessary inputs, nor on how to treat the outputs.

Appendix C Reevaluation of Failed Design Scenarios

The results in Table 5-9 in chapter 5 showed that 22 of designs scenarios failed the requirements of the Verification Method. These scenarios are:

- BE
- UT1 & UT2
- CS1
- CF1, CF2, CF3, CF4 & CF5
- RC1, RC2, RC3, RC4, RC5, RC6, RC7, RC8, RC9 & RC10
- SS
- HS1
- FI1

The original design of the building cannot be verified for compliance and will therefore have to be adjusted in order to pass these design scenarios. Changes for the buildings will thus be proposed, followed by new evaluations of the design scenarios. The assumptions used for application of the Verification Method will be similar to those made in the FPA report with minor changes. The new assumptions are listed in chapter 5 section 5.1.1. The scenarios will be sorted after occupancy category so that all scenarios related to the car park will be dealt with, followed by all scenarios relevant to the ground floor and lastly all scenarios relevant to the upper floors. The FI scenario is general for the entire building, and so it is located at the end of the section.

Because none of the retail area is connected to the staircase, the RC2 does not need to be explicitly modeled. The RC2 scenario will yield the same results as for the CF2 design scenario. The same goes for the RC3 scenario, as it deals with the failure of self-closing doors and the impact that it will have on other evacuating floors. As the

RC3 scenario takes place on the top floor, there is assumed no smoke spillage to the staircases that will impact lower evacuating floors.

In the original report, the scenarios RC6 through RC10 were meant to ensure the robustness of the fire safety design of the building in case of failure of the automatic detection and occupant warning system. However, failure of the self-closing fire safety doors was also included in these scenarios, which yielded very conservative results. The RC6 – RC10 scenarios in this report will therefore be modeled with closed doors, leading to the same ASETs calculated in the corresponding CF-scenarios. However, the RSETs will change as the detection will happen manually instead of automatically.

C.1 Car Park (Level B1 & B2)

In order to reduce the RSETs for the design scenarios in the car park, the standard alarm signal will be replaced by a voice alarm signal on both basement levels. This will reduce the pre-movement time from 60 s to 30 s according to the Verification Method. Additionally, the free width of the exit leading to the staircase will be increased from 0.75 m to 1.1 m.

It was also necessary to increase the ASET. For this purpose, the ceiling height of the basement has been raised from 2.5 m to 2.9 m. Before increasing the ceiling height, a sprinkler system was tried in the zone model for the basement. The sprinkler started after 99 s and did therefore not have a significant effect on the ASET.

In addition to adjusting the layout of the car park, the free widths of the stairways and the doors leading from the office floors to the staircase also had to be increased from 0.75 m to 1.2 m due to a robustness constraint.

C.1.1 CF1 – Challenging Fire in Car Park

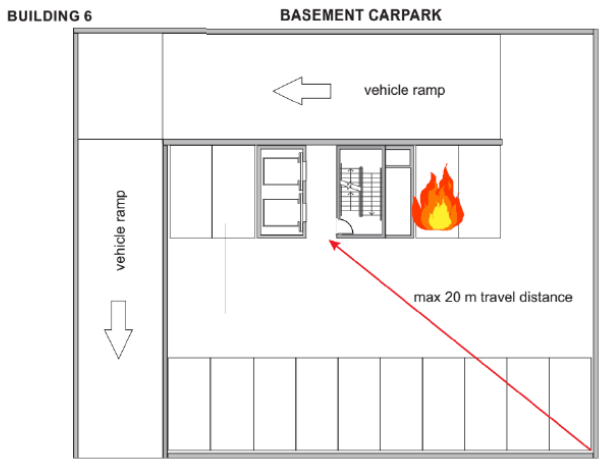


Figure C-1: Location of design fire on the B2 level in the CF1 scenario.

Critical occupants: Occupants on B2.

Table C-1: CF1 fire scenario characteristics.

	New design
Occupancy [persons]	25
Density [persons/m^2]	0.03
Enclosure area [m^2]	500
Maximum horizontal travel distance [m]	20
Number of doors [-]	1
Free width of doors [m]	1.10
Free width of stairs	1.10
Enclosure height [m]	3.1

Table C-2: CF1 fire scenario, RSET summary (manual calculations).

	New design
Detection time [s]	30 (from zone model)
Notification time [s]	30
Pre-movement time [s]	30
Horizontal travel time to exit [s]	17
Flow time [s]	17
Evacuation time [s]	17 (17 = 17)
RSET [s]	107 (30 + 30 + 30 + 17)

Table C-3: CF1 fire scenario, ASET zone model assumptions.

1	Fire modeled in the middle of the car park.
2	Fire burning area increases linearly from 0.09 m^2 (A_{min}) to 30 m^2 (A_{min}) up to the peak heat release rate (20 MW).
3	Car park staircase door open
4	The vehicle rap is modeled as an open window

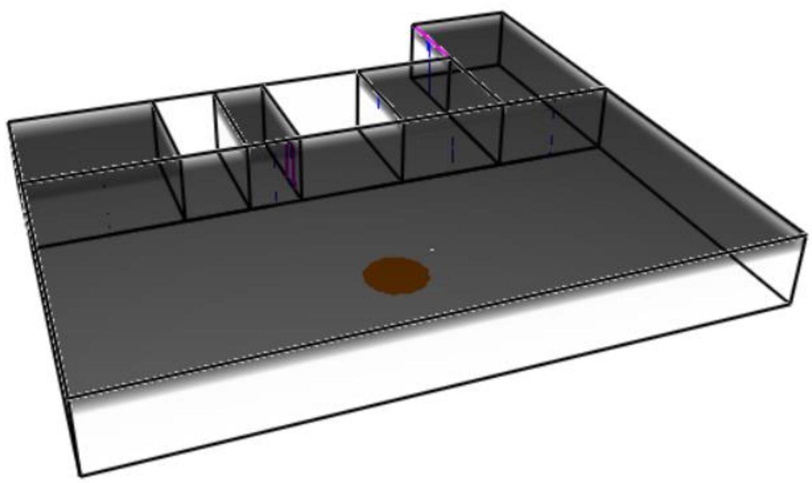


Figure C-2: CFAST model at the time ASET is reached for the B2 floor.

Table C-4: CF1 fire scenario, ASET summary (zone modeling).

Criteria	ASET time [s]
Time for smoke layer to descend to 5% of ceiling height	30
Time for smoke layer to descend to 2 m	110
Time for untenable conditions due to thermal effects (FED greater than 0.3)	110
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	110

Result: ASET/RSET = 110/107 = 1.03

C.1.2 RC1 – Failure of self-closing doors

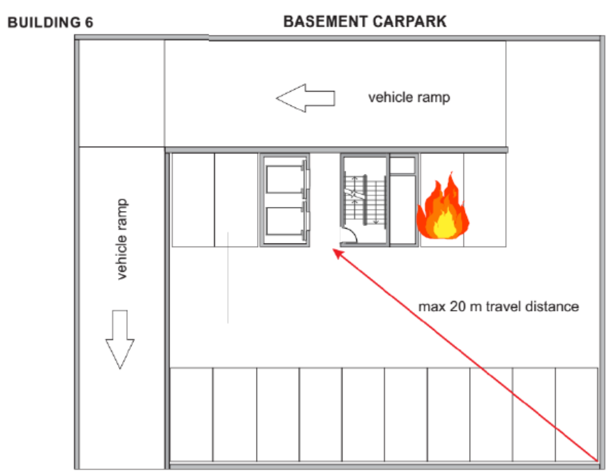


Figure C-3: Location of design fire on the B2 level in the RC1 scenario.

Critical occupants: Occupants on L7.

The issue in this scenario is that the smoke travels from the basement up through the staircase, ending up on the 7^{th} floor. The smoke will cause the staircase to become untenable before all of the occupants from the 7^{th} floor will have evacuated. Therefore the free widths of the stairways and the door leading from the office floor to the staircase have been increased from 0.75 m to 1.2 m, reducing the flow time.

Table C-5: RC1 fire scenario characteristics.

	New design
Occupancy [persons]	62
Density [persons/m^2]	0.10
Enclosure area [m^2]	575
Maximum horizontal travel distance [m]	20
Number of doors/staircases [-]	1
Free width of doors [m]	1.2
Free width of stairs	1.2
Enclosure height [m]	2.7

Table C-6: RC1 fire scenario, RSET summary (manual calculations).

	New design
Detection time [s]	30 (from zone model)
Notification time [s]	30
Pre-movement time [s]	60
Horizontal travel time to exit [s]	17
Vertical travel time to exit [s]	54
Flow time [s]	39
Evacuation time [s]	39 (39 > 17)
RSET [s]	213 (30 + 30 + 60 + 54 + 39)

Table C-7: RC1 fire scenario, ASET zone model assumptions.

1	Fire modeled in the middle of the car park.
2	Fire burning area increases linearly from 0.09 m^2 (A_{min}) to 30 m^2 (A_{min}) up to the peak heat release rate (20 MW).
3	Due to the failure of the self-closers, all the stairs doors are open and the smoke flows throughout the staircase and the other compartments.
4	Model composed of fire compartment (car park) and the building top floor (7th). The two compartments are connected through a staircase modeled as a single-zone compartment (2.5x5.5m) with alternating openings (3.8 m^2) that connect the compartments above and below.
5	Each level of the building is modeled as a rectangular compartment characterized by an effective area. Car park (basement): 500 m^2; office (level 1 to 7): 575 m^2.

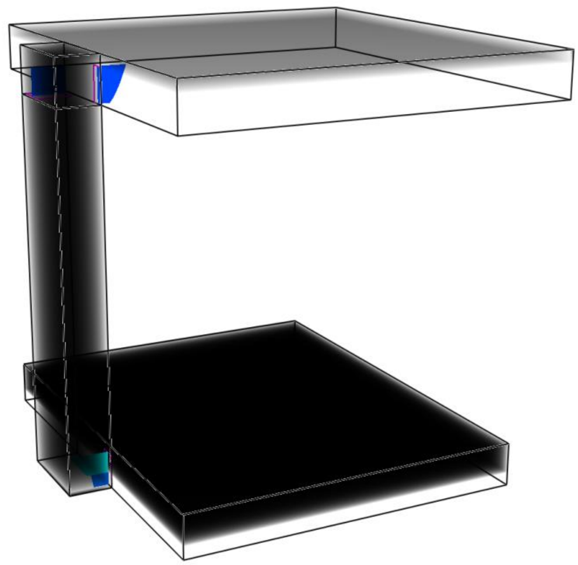


Figure C-4: CFAST model at the time ASET is reached for the RC1 scenario.

Table C-8: RC1 fire scenario, ASET summary (zone modeling).

Criteria	**ASET time [s]**	
	7th floor	**Staircase**
Time for smoke layer to descend to 5% of ceiling height	155	140
Time for smoke layer to descend to 2 m	265	145
Time for untenable conditions due to thermal effects (FED greater than 0.3)	305	250
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	270	215

Result: ASET/RSET = 215/213 = 1.01

C.1.3 RC6 – Failure of Automatic Detection

Critical occupants: Occupants on B2.

As the manual detection time is equal to the automatic detecting time (30 s), this scenario is identical to the CF1 scenario and will therefore yield the same acceptable results.

Result: ASET/RSET = 110/107 = 1.03

C.1.4 SS – Structural Stability of Car Park

The FPA report calculated a time equivalence of 310 s for the car park, because the relatively small ventilation area was outside the range for the time equivalence formula. Instead the lower limit applicable was used to calculate the time equivalence. Also, the VM does not specify the fuel load density for a car park, so instead the fuel load density for retail (900 MJ/m^2) has been chosen as a conservative alternative.

The fire rating of the structures in the car park will have to be minimum 310 min.

C.2 Retail Space (Ground floor)

For the retail space, two different designs of the ground floor have been examined:

(a) 1 exit in each shop with a clear width of 1.50 m, a standard alarm signal, an unchanged ceiling height of 3.0 m and a smoke exhaust system.

(b) 2 exits in each shop with clear widths of 2.30 m, a voice alarm signal and an increased ceiling height of 3.7 m.

The number and widths of the exits will impact the flow/evacuation time, the alarm signal will reduce the assumed pre-movement time, and the increased ceiling height and smoke control system will increase the ASET for the space.

Smoke Control System

Before a smoke exhaust system can be implemented in the CFAST model, the ventilation flow rate has to be calculated. In order to properly exhaust the smoke, the smoke layer depth has to be minimum 20% of the floor-to-ceiling height, thus yielding a minimum 0.6 m smoke layer depth. The design depth will be chosen to 0.8 m.

Convective heat release rate: $\dot{Q}_c = 0.7\dot{Q} = 0.7 \cdot 20{,}000 = 14{,}000$ kW

Smoke layer interface height: $z = 2.2$ m

Mass flow rate: $\dot{m} = 0.071\,\dot{Q}_c^{\frac{1}{3}} z^{\frac{5}{3}} + 0.0018\dot{Q}_c$

$$\dot{m} = 0.071 \cdot 14{,}000^{\frac{1}{3}} \cdot 2.2^{\frac{5}{3}} + 0.0018 \cdot 14{,}000 = 31.57\ \frac{kg}{s}$$

Temperature effect: $\Delta T = \frac{(1-\chi_l)\,\dot{Q}_c}{\dot{m}\,c_p} = \frac{(1-0.7)14{,}000}{31.57 \cdot 1.0} = 190$ K

Adjusting the density: $\frac{\rho}{\rho_0} = \frac{T_0}{T} \rightarrow \rho = \frac{T_0}{T}\rho_0 = \frac{293\text{ K}}{483\text{ K}} 1.2\ \frac{kg}{m^3} = 0.73\,\frac{kg}{m^3}$

Volumetric flow rate: $\dot{V} = \frac{\dot{m}}{\rho} = \frac{31.57}{0.73} = 43.4\ \frac{m^3}{s}$

In order to avoid plugholing, a maximum flow rate per vent must be calculated:

Temperature difference: $T_s - T_0 = \frac{\dot{Q}_c}{\rho \dot{V} c_p} = \frac{14{,}000}{0.73 \cdot 43.4 \cdot 1.0} = 443$ K

Smoke layer depth: $d = 0.8$ m

Maximum flow rate per vent: $\dot{V}_{max} = 4.16\left(\frac{d^2(T_s - T_0)}{T_0}\right)^{½} = 4.16\left(\frac{0.8^2(443)}{293}\right)^{½} = 2.9\,\frac{m^3}{s}$

Total number of inlets: $\frac{\dot{V}}{V_{max}} = \frac{43.4}{2.9} \approx 15$ vents

Minimum separation of inlets: $S_{min} = 0.9\dot{V}^{½} = 0.9(2.9)^{½} = 1.5$ m

Fire Suppression System:

A sprinkler system was also tried for the ground floor. The VM prescribes detector criteria for standard response and a quick response sprinklers. A quick response sprinkler with the following criteria has been tried for the retail area:

- RTI = 50 $m^{½}s^{½}$
- Actuation temperature = 68^{o}C
- Radial distance from fire = 3.25 m
- Distance below ceiling = 30 mm

It was found that the sprinklers would actuate too late to affect the ASET in any significant way.

All design scenarios have been demonstrated for the larger one of the two retail spaces, but the final design result will be applied to both retail spaces.

C.2.1 BE2 – Blocked Exit

This scenario was not originally a part of the FPA report, but will be applied to the retail area as it is required by the Verification Method for egress routes that serve more than 50 occupants. The VM does not explicitly require an ASET/RSET analysis of this scenario, but it does state that in the event of a fire blocking an exit, the number of exits and total exit width must be sufficient for occupants to escape before the ASET is reached. The ASET is limited by the same severe design fire that is used in the Challenging Fire (CF) scenarios. Therefore this scenario basically requires another exit from the retail spaces in addition to the number of exits that the analysis of the CF2 scenario will entail for the ground floor.

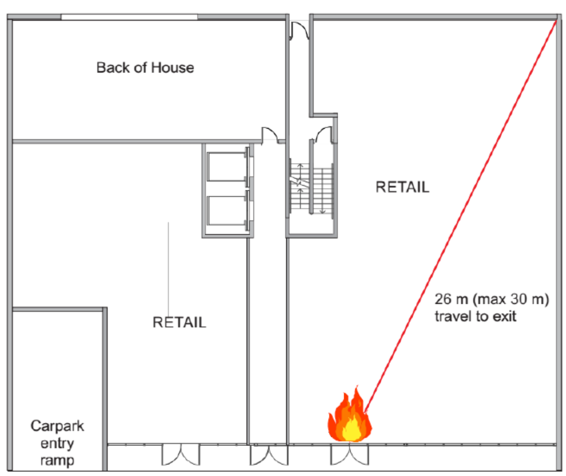


Figure C-5: Location of the design fire in the BE2 scenario.

The outcome of this scenario is either (a) or (b). If the analysis of the CF2 scenario results yields that:

(a) Only one exit is necessary in order for the ASET > RSET, then two exits will be required for the final building design of the ground floor.

(b) Two exits are necessary in order for the ASET > RSET, then three exits will be required for the final building design of ground floor.

C.2.2 UT2 - Fire in a Storage Room in Retail Area

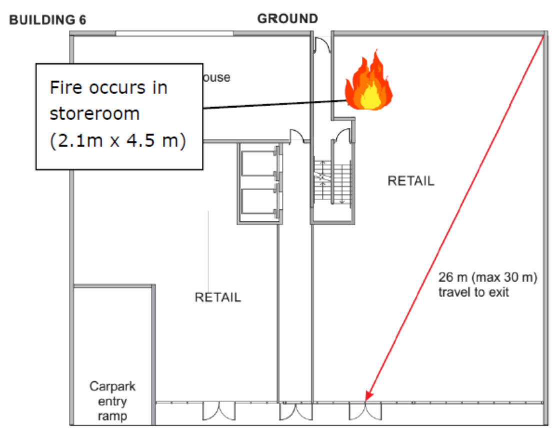


Figure C-6: Location of the design fire in the UT2 scenario. The fire is located in a storage room.

Table C-9: UT2 fire scenario characteristics.

	Design (a)	**Design (b)**
Occupancy [persons]	120	120
Density [persons/m^2]	0.33	0.33
Enclosure area [m^2]	350	350
Maximum horizontal travel distance [m]	30	16
Number of doors [-]	1	2
Free width of doors [m]	1.50	2.30
Enclosure height [m]	3.0	3.0

Table C-10: UT2 fire scenario, RSET summary (manual calculations).

	Design (a)	**Design (b)**
Detection time [s]	20	250
Notification time [s]	30	30
Pre-movement time [s]	60	30
Horizontal travel time to exit [s]	25	13
Flow time [s]	60	20
Evacuation time [s]	60 (60 > 25)	20 (20 > 13)
RSET [s]	170 (20 + 30 + 60 + 30)	100 (20 + 30 + 30 + 20)

Table C-11: UT 2 fire scenario, ASET zone model assumptions.

1	Fire modeled in a storage room of the retail area.
2	Fire burning area increases linearly from 0.09 m^2 (A_{min}) to 10 m^2 (A_{min}) up to the peak heat release rate (20 MW).
3	Retail area exit doors open

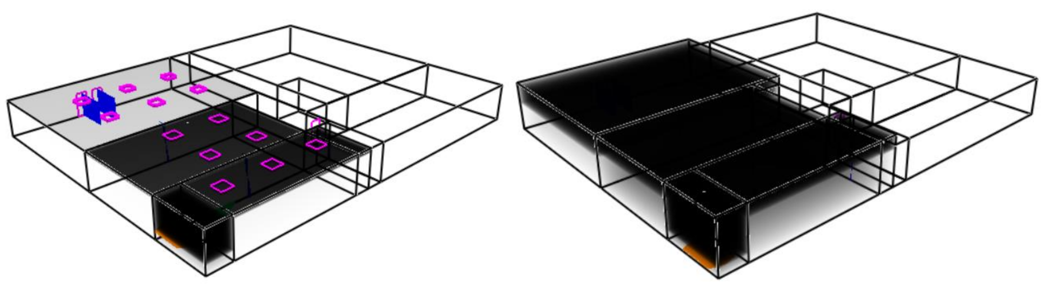


Figure C-7: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right.

Table C-12: UT2 fire scenario, ASET summary (zone modeling)

Criteria	**ASET time [s]**	
	Design (a)	**Design (b)**
Automatic detection time	20	20
Time for smoke layer to descend to 2 m	260	160
Time for untenable conditions due to thermal effects (FED greater than 0.3)	180	160
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	260	150

Results:

(a) ASET/RSET = 180/170 = 1.06
(b) ASET/RSET = 150/100 = 1.50

C.2.3 CF2 – Challenging Fire in Retail Area

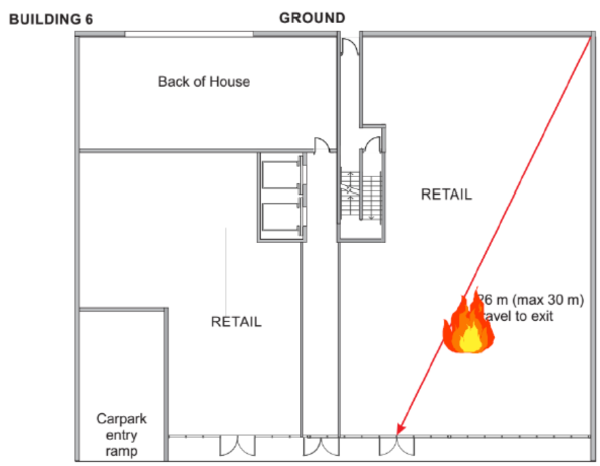


Figure C-8: Location of design fire on the ground floor in the CF2 scenario.

Table C-13: CF2 fire scenario characteristics.

	Design (a)	Design (b)
Occupancy [persons]	120	120
Density [persons/m^2]	0.33	0.33
Enclosure area [m^2]	350	350
Maximum horizontal travel distance [m]	30	16
Number of doors [-]	1	2
Free width of doors [m]	1.50	2.30
Enclosure height [m]	3.0	3.0

Table C-14: CF2 fire scenario, RSET summary (manual calculations).

	Design (a)	**Design (b)**
Detection time [s]	20	20
Notification time [s]	30	30
Pre-movement time [s]	60	30
Horizontal travel time to exit [s]	25	13
Flow time [s]	60	20
Evacuation time [s]	60 (60 > 25)	20 (20 > 13)
RSET [s]	170 (20 + 30 + 60 + 30)	100 (20 + 30 + 30 + 20)

Table C-15: CF 2 fire scenario, ASET zone model assumptions.

1	Fire modeled in the middle of the retail area.
2	Fire burning area increases linearly from 0.09 m^2 (A_{min}) to 30 m^2 (A_{min}) up to the peak heat release rate (20 MW).
3	Retail area exit doors open

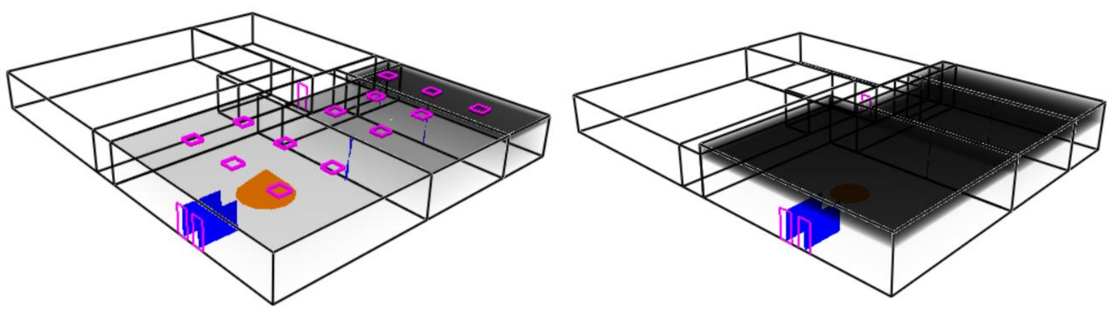


Figure C-9: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right.

Table C-16: CF2 fire scenario, ASET summary (zone modeling).

Criteria	**ASET time [s]**	
	Design (a)	**Design (b)**
Automatic detection time	20	20
Time for smoke layer to descend to 2 m	250	115
Time for untenable conditions due to thermal effects (FED greater than 0.3)	230	150
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	250	115

Results:

(a) ASET/RSET = 230/170 = 1.35
(b) ASET/RSET = 115/100 = 1.15

C.2.4 RC2 – Failure of Self-closing Doors

Because none of the retail area is connected to the staircase, the RC2 does not need to be explicitly modeled. The RC2 scenario will yield the same results as for the CF2 design scenario.

Results:

(a) ASET/RSET = 230/170 = 1.35
(b) ASET/RSET = 115/100 = 1.15

C.2.5 RC7 – Failure of Detection System

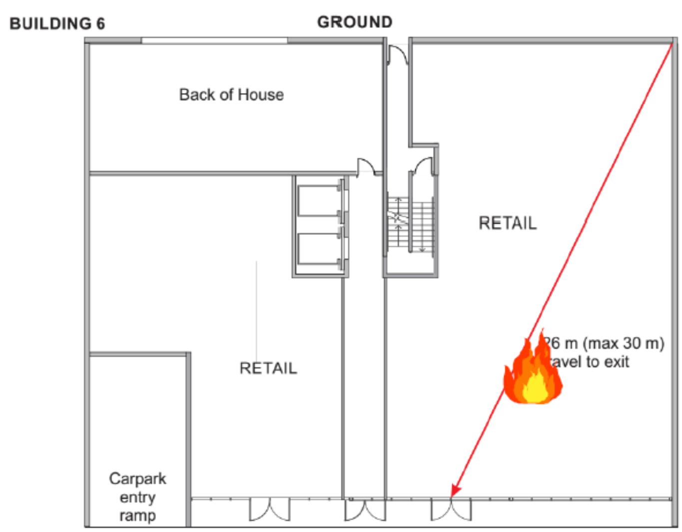


Figure C-10: Location of the design fire on the ground floor in the RC7 scenario.

Table C-17: RC7 fire scenario characteristics.

	Design (a)	**Design (b)**
Occupancy [persons]	120	120
Density [persons/m^2]	0.33	0.33
Enclosure area [m^2]	350	350
Maximum horizontal travel distance [m]	30	16
Number of doors [-]	1	2
Free width of doors [m]	1.50	2.30
Enclosure height [m]	3.0	3.0

Table C-18: RC7 fire scenario, RSET summary (manual calculations).

	Design (a)	**Design (b)**
Detection time [s]	25 (Manual detection)	30 (Manual detection)
Notification time [s]	30	30
Pre-movement time [s]	60	30
Horizontal travel time to exit [s]	25	13
Flow time [s]	60	20
Evacuation time [s]	60 (60 > 25)	20 (20 > 13)
RSET [s]	175 (25 + 30 + 60 + 30)	110 (30 + 30 + 30 + 20)

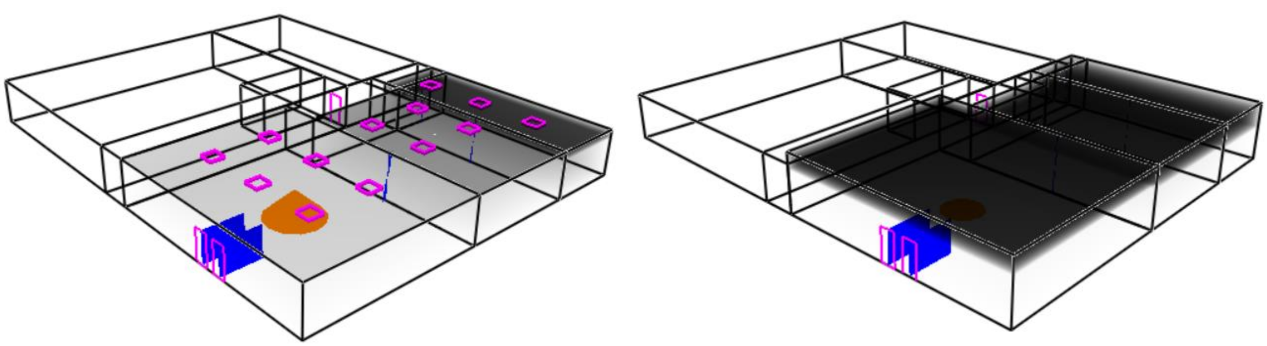


Figure C-11: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right.

Table C-19: RC7 fire scenario, ASET summary (zone modeling).

Criteria	ASET time [s]	
	Design (a)	Design (b)
Manual detection time	25	30
Time for smoke layer to descend to 2 m	250	115
Time for untenable conditions due to thermal effects (FED greater than 0.3)	230	150
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	250	115

Results:

(a) ASET/RSET = 230/175 = 1.31
(b) ASET/RSET = 115/110 = 1.05

C.3 Office floors (L1-L7)

The upper floors have been demonstrated for two different design options, (a) and (b):

(a) 1 staircase of 1.2 m clear width (1 door of 1.2 m clear width), a standard alarm signal and an increased ceiling height of 3.1 m.

(b) 2 staircases of 1.4 m clear widths (2 doors of 1.4 m clear widths), a standard alarm signal and an unchanged ceiling height of 2.7 m.

The minimum width of 1.2 m of the single staircase in solution (a) is required by the RC1 design scenario for a fire in the car park. Increasing the clear widths of the exit components reduces the evacuation time. A voice alarm signal will not be necessary for the office floors, as people are assumed aware, awake and familiar with the building, for which case the VM doesn't differ between alarm signal types when determining the pre-movement times. Increasing the ceiling height increases the ASET.

C.3.1 BE1 - Fire blocks exit on a typical office floor level

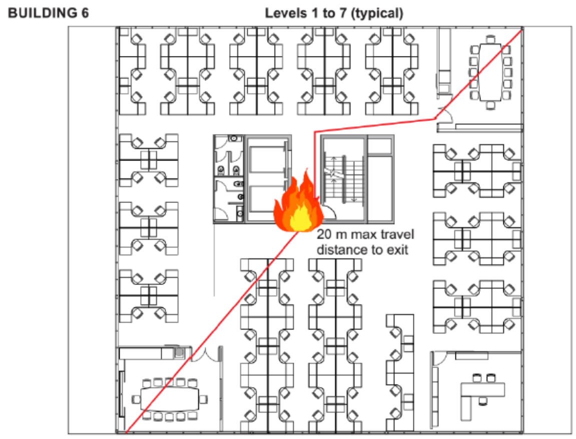


Figure C-12: Location of the design fire on the office floor in the BE1 scenario.

This scenario was created, but not analyzed in the initial VM application of the building due to the fact that there was only one exit on the office floors, inevitably leading to casualties. The VM does not explicitly require an ASET/RSET analysis of this scenario, but it does state that in the event of a fire blocking an exit, the number of exits and total exit width must be sufficient for occupants to escape before the ASET is reached. This ASET is limited by the same severe design fire that is also used in the Challenging Fire (CF) scenarios. The outcome of this scenario therefore depends on the analysis of the Challenging Fire scenario for the office floors, CF3, CF4 and CF5, and the result will thus be either (a) or (b) listed below.

If the analyses of the CF3, CF4 and CF5 scenarios yield that:

(a) Only one staircase is necessary in order for the ASET > RSET, then two staircases will be required for the final building design of the office floors.

(b) Two staircases are necessary in order for the ASET > RSET, then three staircases will be required for the final building design of the office floors.

C.3.2 UT1 – Fire in Unoccupied Room

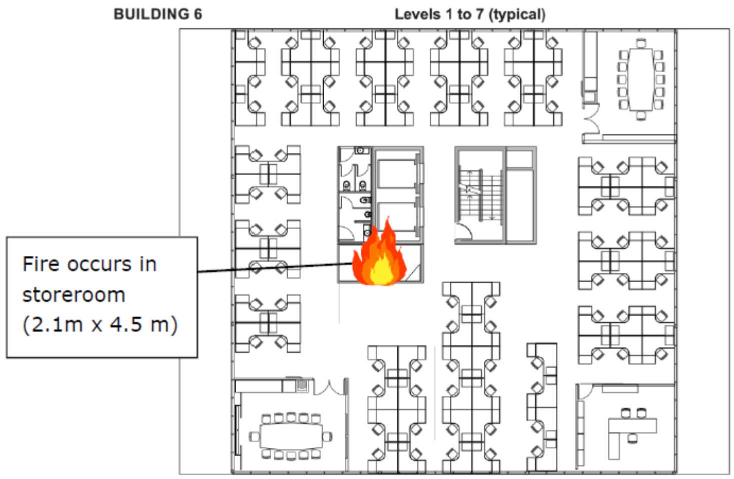


Figure C-13: Location of the design fire on the office floor in the UT1 scenario. The fire is located in a storage room.

Critical occupants: Occupants on a typical office floor.

Table C-20: UT1 fire scenario characteristics.

	Design (a)	Design (b)
Critical occupants	Occupants in a typical office level	
Occupancy [persons]	62	
Density [persons/m^2]	0.10	
Enclosure area [m^2]	575	
Maximum horizontal travel distance [m]	20	20
Number of doors/staircases [-]	1	2
Free width of doors [m]	1.2	1.4
Free width of stairs	1.2	1.4
Enclosure height [m]	3.1	2.7

Table C-21: UT1 fire scenario, RSET summary (manual calculations).

	Design (a)	Design (b)
Detection time [s]	25	25
Notification time [s]	30	30
Pre-movement time [s]	30	30
Horizontal travel time to exit [s]	17	17
Vertical travel time to exit [s]	0	0
Flow time [s]	39	17
Evacuation time [s]	39 (39 > 17)	17 (17 = 17)
RSET [s]	124 (25 + 30 + 30 + 39)	102 (25 + 30 + 30 + 17)

Table C-22: UT 1 fire scenario, ASET zone model assumptions.

1	Fire modeled in a storage room in a typical office level.
2	Fire burning area increases linearly from 0.09 m^2 (A_{min}) to 10 m^2 (A_{min}) up to the peak heat release rate (20 MW).
3	Storage room door opened.
4	Conference and meeting rooms doors open
5	No open windows in the library/office area
6	The access door to the staircase is open

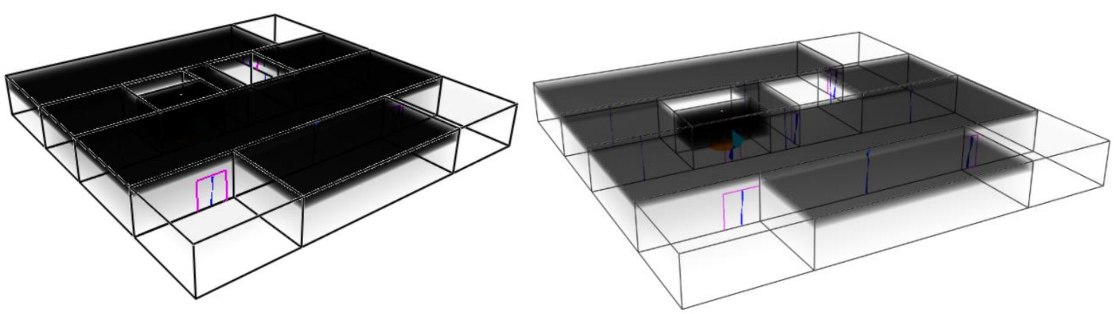


Figure C-14: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right.

Table C-23: UT1 fire scenario, ASET summary (zone modeling).

Criteria	**ASET time [s]**	
	Design (a)	**Design (b)**
Automatic detection time	25	25
Time for smoke layer to descend to 2 m	160	150
Time for untenable conditions due to thermal effects (FED greater than 0.3)	160	170
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	160	150

Results:

(a) ASET/RSET = 160/124 = 1.29
(b) ASET/RSET = 150/102 = 1.47

C.3.3 CS1 – Fire in Concealed Space

Critical occupants: Occupants on a typical office floor.

In the FPA report, the ASET/RSET analysis of this scenario was completely identical to the ASET/RSET carried out for the CF3 design scenario. Therefore this scenario is considered passed, when the CF3 design scenario is passed, presupposing that the concealed space has been provided with an automatic smoke detection system.

Results:

(a) ASET/RSET = 130/124 = 1.05
(b) ASET/RSET = 100/97 = 1.03

C.3.4 CF – Challenging Fire Design Scenarios

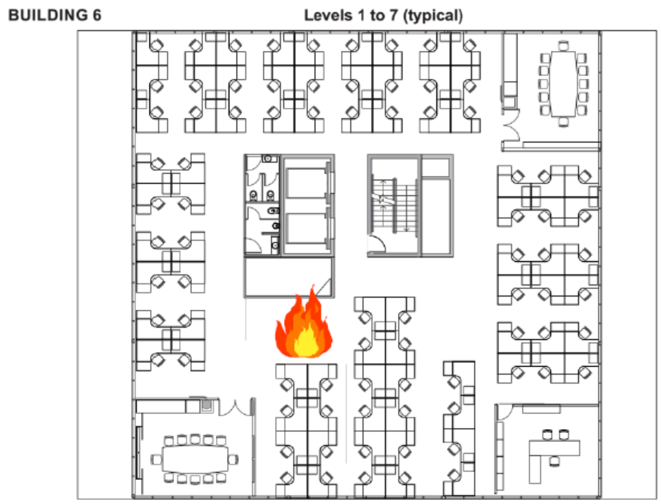


Figure C-15: Location of the design fire on the office floor in the CF scenarios.

The CF3, CF4 and CF5 scenarios all have common values for the RSET based on the highest measured value for the automatic detection time.

Table C-24: CF3-CF5 fire scenario characteristics.

	Design (a)	**Design (b)**
Occupancy [persons]	62	
Density [persons/m^2]	0.10	
Enclosure area [m^2]	575	
Maximum horizontal travel distance [m]	20	20
Number of doors/staircases [-]	1	2
Free width of doors [m]	1.2	1.4
Free width of stairs	1.2	1.4
Enclosure height [m]	3.1	2.7

Table C-25: CF3-CF5 fire scenario, RSET summary (manual calculations).

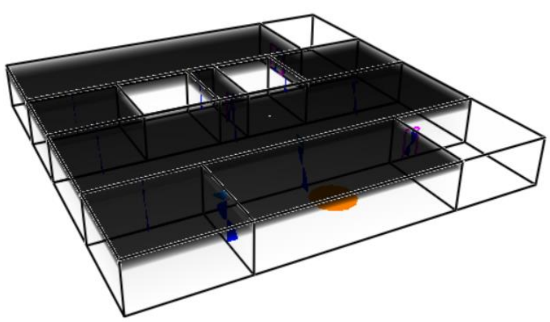
	Design (a)	**Design (b)**
Detection time [s]	25	20
Notification time [s]	30	30
Pre-movement time [s]	30	30
Horizontal travel time to exit [s]	17	17
Vertical travel time to exit [s]	0	0
Flow time [s]	39	17
Evacuation time [s]	39 (39 > 17)	17 (17 = 17)
RSET [s]	124 (25 + 30 + 30 + 39)	97 (20 + 30 + 30 + 17)

Table C-26: CF 5 fire scenario, ASET zone model assumptions.

1	Fire modeled in the middle of the office area.
2	Fire burning area increases linearly from 0.09 m^2 (A_{min}) to 30 m^2 (A_{min}) up to the peak heat release rate (20 MW).
3	Conference and meeting room doors open
4	No opened windows in the library/office area.
5	The access doors to the staircase is open
6	The 6^{th} and 7^{th} office levels are connected through an opening (6.5x5.5m) representing the internal open stairway.

C.3.4.1 CF3 – Challenging Fire on Top Floor

Critical occupants: Occupants on L7.



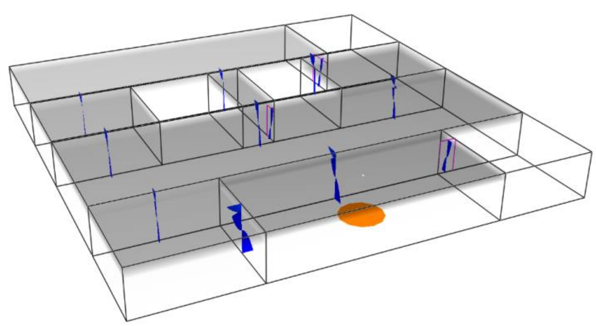


Figure C-16: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right.

Table C-27: CF3 fire scenario, ASET summary (zone modeling).

Criteria	ASET time [s]	
	Design (a)	**Design (b)**
Automatic or manual detection time	25	20
Time for smoke layer to descend to 2 m	130	100
Time for untenable conditions due to thermal effects (FED greater than 0.3)	150	155
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	130	100

Results:

(c) ASET/RSET = 130/124 = 1.05
(d) ASET/RSET = 100/97 = 1.03

C.3.4.2 CF4 – Challenging Fire in Library

Critical occupants: Occupants on L1

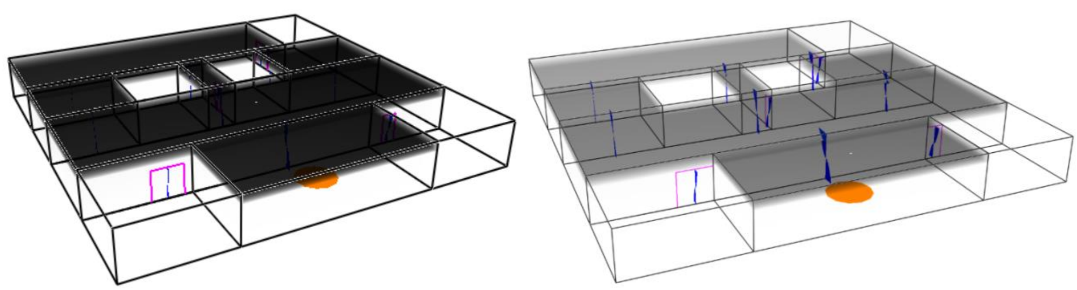


Figure C-17: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right.

Table C-28: CF4 fire scenario, ASET summary (zone modeling).

Criteria	ASET time [s]	
	Design (a)	**Design (b)**
Automatic/Manual detection time	25	20
Time for smoke layer to descend to 2 m	125	110
Time for untenable conditions due to thermal effects (FED greater than 0.3)	140	150
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	125	110

Results:

(a) ASET/RSET = 125/124 = 1.01
(b) ASET/RSET = 110/97 = 1.13

C.3.4.3 CF5 – Challenging Fire on 6th floor

Critical occupants: Occupants on L6.

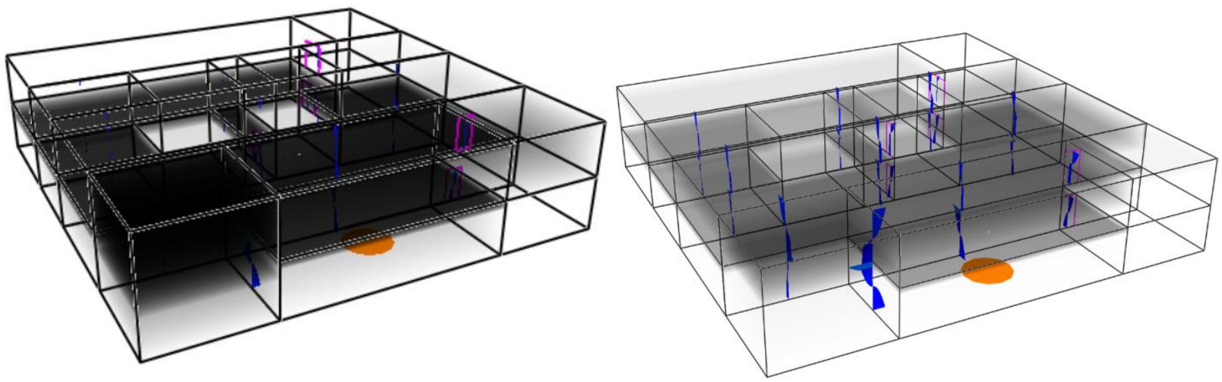


Figure C-18: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right.

Table C-29: CF5 fire scenario, ASET summary (zone modeling).

Criteria	ASET time [s]	
	Design (a)	Design (b)
Automatic/Manual detection time	20	20
Time for smoke layer to descend to 2 m	130	60
Time for untenable conditions due to thermal effects (FED greater than 0.3)	160	215
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	130	125

Results:

(a) ASET/RSET = 130/124 = 1.05
(b) ASET/RSET = 125/97 = 1.29

C.3.5 RC – Robustness Check

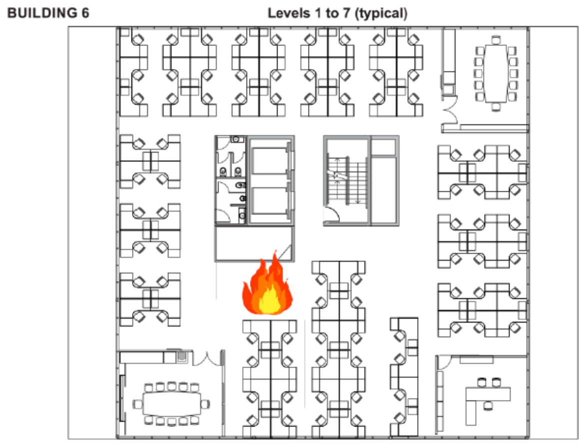


Figure C-19: Location of design fire on the office floor for the RC3 – RC5 scenarios.

C.3.5.1 RC3 – Failure of Self-closing Doors

The failure of the self-closers of stair doors is not relevant for this scenario, because the design fire is placed on the top floor. Therefore there is no smoke spillage in the staircases acting as the main egress paths for the occupants of the below levels.

C.3.5.2 RC4 – Failure of Self-closing Doors

Critical occupants: Occupants on L7.

Table C-30: RC4 fire scenario characteristics.

	Design (a)	Design (b)
Occupancy [persons]	62	
Density [persons/m^2]	0.10	
Enclosure area [m^2]	575	
Maximum horizontal travel distance [m]	20	20
Number of doors/staircases [-]	1	2
Free width of doors [m]	1.2	1.4
Free width of stairs	1.2	1.4
Enclosure height [m]	3.1	2.7

Table C-31: RC4 fire scenario, RSET summary (manual calculations).

	Design (a)	Design (b)
Detection time [s]	20	20
Notification time [s]	30	30
Pre-movement time [s]	60	60
Horizontal travel time to exit [s]	17	17
Vertical travel time to exit [s]	54	54
Flow time [s]	39	17
Evacuation time [s]	39 (39 > 17)	17 (17 = 17)
RSET [s]	203 (20+30+60+54+39)	181 (20+30+60+54+17)

Table C-32: RC 4 fire scenario, ASET zone model assumptions.

1	Fire modeled in the middle of the office area.
2	Fire burning area increases linearly from 0.09 m^2 (A_{min}) to 30 m^2 (A_{min}) up to the peak heat release rate (20 MW).
3	Due to the failure of the self-closers, all the stairs doors are opened and the smoke flows throughout the staircase and the other compartments.
4	Model composed of fire compartment (library in office area, 1st floor) and the building top floor (7th). The two compartments are connected through a staircase modeled as a single-zone compartment (2.5x5.5m) with alternating openings (3.8 m^2) that connect the compartments above and below.
5	Each level of the building is modeled as a rectangular compartment characterized by an effective area. Office (level 1 to 7): 575 m^2.

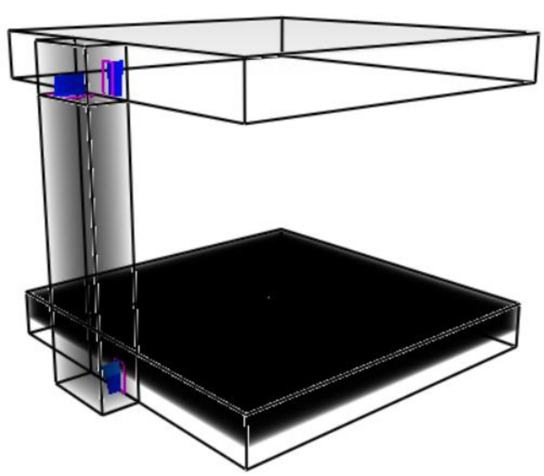


Figure C-20: CFAST model at the time ASET is reached for design (a)

Table C-33: RC4 fire scenario, ASET summary (zone modeling) for design (a).

Criteria	ASET time [s]	
	7th floor	Staircase
Time for smoke layer to descend to 5% of ceiling height	170	155
Time for smoke layer to descend to 2 m	330	165
Time for untenable conditions due to thermal effects (FED greater than 0.3)	310	245
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	330	210

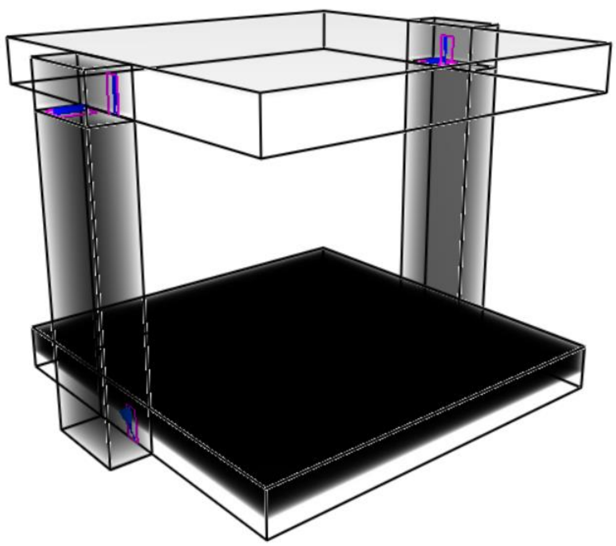


Figure C-21: CFAST model at the time ASET is reached for design (b).

Table C-34: RC4 fire scenario, ASET summary (zone modeling) for design (b).

Criteria	ASET time [s]	
	7th floor	Staircase
Time for smoke layer to descend to 5% of ceiling height	180	155
Time for smoke layer to descend to 2 m	280	160
Time for untenable conditions due to thermal effects (FED greater than 0.3)	280	245
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	250	200

Results:

(a) ASET/RSET = 210/203 = 1.04

(b) ASET/RSET = 200/181 = 1.11

C.3.5.3 RC5 – Failure of Self-closing Doors

Critical occupants: Occupants on L7.

Table C-35: RC5 fire scenario characteristics.

	Design (a)	**Design (b)**
Occupancy [persons]	62	
Density [persons/m^2]	0.10	
Enclosure area [m^2]	575	
Maximum horizontal travel distance [m]	20	20
Number of doors/staircases [-]	1	2
Free width of doors [m]	1.2	1.4
Free width of stairs	1.2	1.4
Enclosure height [m]	3.1	2.7

Table C-36: RC5 fire scenario, RSET summary (manual calculations).

	Design (a)	**Design (b)**
Detection time [s]	20	20
Notification time [s]	30	30
Pre-movement time [s]	60	60
Horizontal travel time to exit [s]	17	17
Vertical travel time to exit [s]	54	54
Flow time [s]	39	17
Evacuation time [s]	39 (39 > 17)	17 (17 = 17)
RSET [s]	203 (20+30+60+54+39)	181 (20+30+60+54+17)

Table C-37: RC 5 fire scenario, ASET zone model assumptions.

1	Fire modeled in the middle of the office area.
2	Fire burning area increases linearly from 0.09 m^2 (A_{min}) to 30 m^2 (A_{min}) up to the peak heat release rate (20 MW).
3	Due to the failure of the self-closers, all the stairs doors are open and the smoke flows throughout the staircase and the other compartments.
4	Model composed of the top 2 building levels (6^{th} and 7^{th}) connected through the staircase and stairs doors.
5	Each staircase level modeled as a single-zone compartment (2.5x5.5m) with alternating openings (3.8 m^2) that connect the compartments above and below.
6	Each office level of the building is modeled as a rectangular compartment characterized by an effective area equal to 575 m^2.
7	The 6^{th} and 7^{th} office levels are connected through an opening (6.5x5.5m) representing the internal open stairway.

Figure C-22: CFAST model at the time ASET is reached for design (a).

Table C-38: RC5 fire scenario, ASET summary (zone modeling) for design (a).

Criteria	**ASET time [s]**	
	7th floor	**Staircase**
Time for smoke layer to descend to 5% of ceiling height	100	30
Time for smoke layer to descend to 2 m	210	75
Time for untenable conditions due to thermal effects (FED greater than 0.3)	225	260
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	210	245

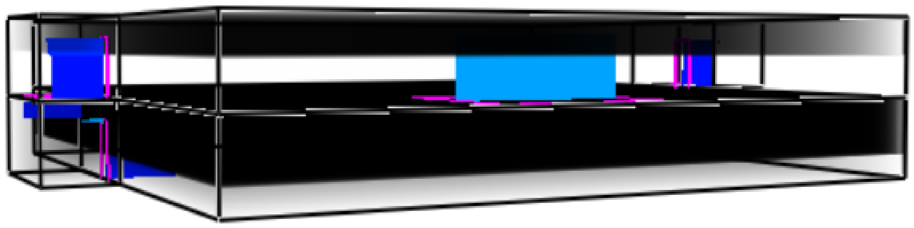


Figure C-23: CFAST model at the time ASET is reached for design (b).

Table C-39: RC5 fire scenario ASET summary (zone modeling) for design (b)

Criteria	**ASET time [s]**	
	7th floor	**Staircase**
Time for smoke layer to descend to 5% of ceiling height	100	20
Time for smoke layer to descend to 2 m	170	60
Time for untenable conditions due to thermal effects (FED greater than 0.3)	230	245
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	230	240

Results:

(a) ASET/RSET = 245/181 = 1.35
(b) ASET/RSET = 240/203 = 1.18

C.3.6 RC8 – Failure of Detection System

Critical occupants: Occupants on L7.

Table C-40: RC8 fire scenario characteristics.

	Design (a)	**Design (b)**
Occupancy [persons]	62	
Density [persons/m^2]	0.10	
Enclosure area [m^2]	575	
Maximum horizontal travel distance [m]	20	20
Number of doors/staircases [-]	1	2
Free width of doors [m]	1.2	1.4
Free width of stairs	1.2	1.4
Enclosure height [m]	3.1	2.7

Table C-41: RC8 fire scenario, RSET summary (manual calculations).

	Design (a)	**Design (b)**
Detection time [s]	25	20
Notification time [s]	30	30
Pre-movement time [s]	30	30
Horizontal travel time to exit [s]	17	17
Vertical travel time to exit [s]	0	0
Flow time [s]	39	17
Evacuation time [s]	39 (39 > 17)	17 (17 = 17)
RSET [s]	124 (25 + 30 + 30 + 39)	97 (20 + 30 + 30 + 17)

Table C-42: RC 8 fire scenario, ASET zone model assumptions.

1	Fire modeled in the middle of the office area.
2	Fire burning area increases linearly from 0.09 m^2 (A_{min}) to 30 m^2 (A_{min}) up to the peak heat release rate (20 MW).
3	Conference and meeting room doors open
4	No open windows in the library/office area
5	Failure of automatic detection and occupant warning system

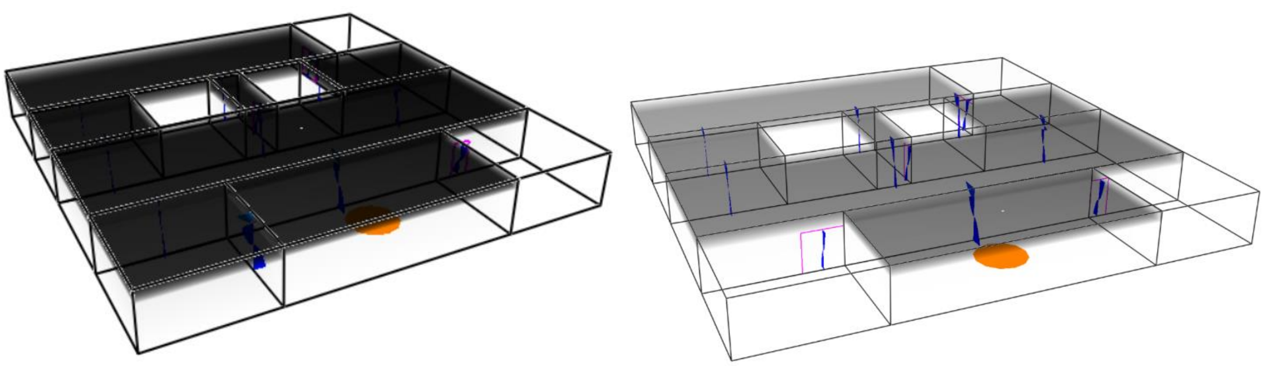


Figure C-24: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right.

Table C-43: RC8 fire scenario, ASET summary (zone modeling).

Criteria	**ASET time [s]**	
	Design (a)	**Design (b)**
Manual detection time	25	20
Time for smoke layer to descend to 2 m	130	100
Time for untenable conditions due to thermal effects (FED greater than 0.3)	150	155
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	130	100

Results:

(a) ASET/RSET = 130/124 = 1.05
(b) ASET/RSET = 100/97 = 1.03

C.3.7 RC9 – Failure of Detection System

Critical occupants: Occupants on L1.

Table C-44: RC9 fire scenario characteristics.

	Design (a)	**Design (b)**
Occupancy [persons]	62	
Density [persons/m^2]	0.10	
Enclosure area [m^2]	575	
Maximum horizontal travel distance [m]	20	20
Number of doors/staircases [-]	1	2
Free width of doors [m]	1.2	1.4
Free width of stairs	1.2	1.4
Enclosure height [m]	3.1	2.7

Table C-45: RC9 fire scenario RSET summary (manual calculations).

	Design (a)	Design (b)
Detection time [s]	25	20
Notification time [s]	30	30
Pre-movement time [s]	30	30
Horizontal travel time to exit [s]	17	17
Vertical travel time to exit [s]	0	0
Flow time [s]	39	17
Evacuation time [s]	39 (39 > 17)	17 (17 = 17)
RSET [s]	124 (25 + 30 + 30 + 39)	97 (20 + 30 + 30 + 17)

Table C-46: RC 9 fire scenario, ASET zone model assumptions.

1	Fire modeled in the middle of the office area.
2	Fire burning area increases linearly from 0.09 m^2 (A_{min}) to 30 m^2 (A_{min}) up to the peak heat release rate (20 MW).
3	Conference and meeting room doors open
4	No open windows in the library/office area
5	Failure of automatic detection and occupant warning system

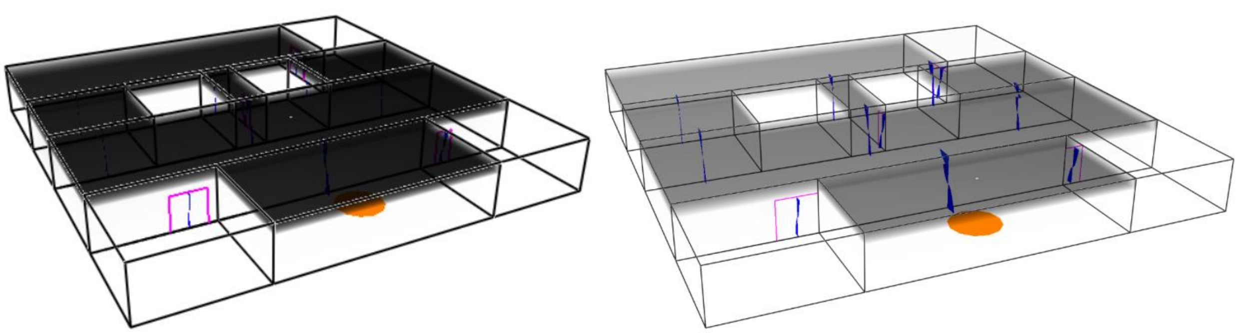


Figure C-25: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right.

Table C-47: RC9 fire scenario ASET summary (zone modeling)

Criteria	ASET time [s]	
	Design (a)	**Design (b)**
Manual detection time	25	20
Time for smoke layer to descend to 2 m	125	110
Time for untenable conditions due to thermal effects (FED greater than 0.3)	140	150
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	125	110

Results:

(c) ASET/RSET = 125/124 = 1.01
(d) ASET/RSET = 110/97 = 1.13

C.3.8 RC10 – Failure of Detection System

Critical occupants: Occupants on L6.

Table C-48: RC10 fire scenario characteristics.

	Design (a)	**Design (b)**
Occupancy [persons]	62	
Density [persons/m^2]	0.10	
Enclosure area [m^2]	575	
Maximum horizontal travel distance [m]	20	20
Number of doors/staircases [-]	1	2
Free width of doors [m]	1.2	1.4
Free width of stairs	1.2	1.4
Enclosure height [m]	3.1	2.7

Table C-49: RC10 fire scenario, RSET summary (manual calculations).

	Design (a)	**Design (b)**
Detection time [s]	20	20
Notification time [s]	30	30
Pre-movement time [s]	30	30
Horizontal travel time to exit [s]	17	17
Vertical travel time to exit [s]	0	0
Flow time [s]	39	17
Evacuation time [s]	39 (39 > 17)	17 (17 = 17)
RSET [s]	119 (20 + 30 + 30 + 39)	97 (20 + 30 + 30 + 17)

Table C-50: RC10 fire scenario, ASET zone model assumptions.

1	Fire modeled in the middle of the office area.
2	Fire burning area increases linearly from 0.09 m^2 (A_{min}) to 30 m^2 (A_{min}) up to the peak heat release rate (20 MW).
3	Model composed of the top 2 building levels (6^{th} and 7^{th}) connected through the staircase and stairs doors.
4	Each staircase level modeled as a single-zone compartment (2.5x5.5m) with alternating openings (3.8 m^2) that connect the compartments above and below.
5	Each office level of the building is modeled as a rectangular compartment characterized by an effective area equal to 575 m^2.
6	The 6^{th} and 7^{th} office levels are connected through an opening (6.5x5.5m) representing the internal open stairway.
7	Failure of automatic detection and occupant warning system

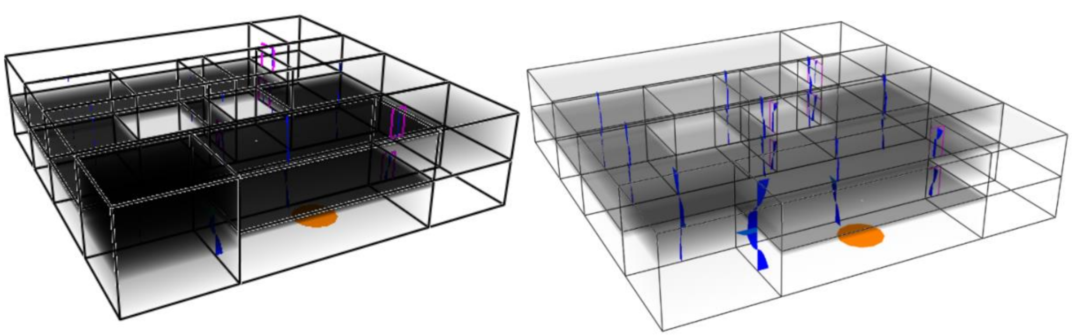


Figure C-26: CFAST models at the time ASET is reached for design (a) to the left and design (b) to the right.

Table C-51: RC10 fire scenario, ASET summary (zone modeling).

Criteria	**ASET time [s]**	
	Design (a)	**Design (b)**
Manual detection time	20	20
Time for smoke layer to descend to 2 m	130	60
Time for untenable conditions due to thermal effects (FED greater than 0.3)	160	215
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	130	125

Results:

(e) ASET/RSET = 130/119 = 1.09
(f) ASET/RSET = 125/97 = 1.29

C.3.9 HS1 – Horizontal Fire Spread

The horizontal spread is calculated using a radiant heat transfer calculation according to the following equation:

$$\dot{q}''_{rad} = \epsilon \sigma A_d T_S^4$$

Where

- Radiant heat flux: $\dot{q}''_{rad}$
- Emissivity: $\epsilon = 0.9$ (Assumed in FPA report)
- Stefan-Boltzmann constant: $\sigma = 5.67 \cdot 10^{-8} \frac{W}{m^2 K^4}$
- View factor: A_d
- Temperature: $T_S = 1000^0 C$ (Assumed in FPA report)

The view factor is calculated as:

$$A_d = \frac{1}{2\pi}\left(\frac{X}{\sqrt{1+X^2}}\tan^{-1}\frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\frac{X}{\sqrt{1+Y^2}}\right)$$

Where $X = \frac{a}{c}$ and $Y = \frac{b}{c}$ based on the diagram below.

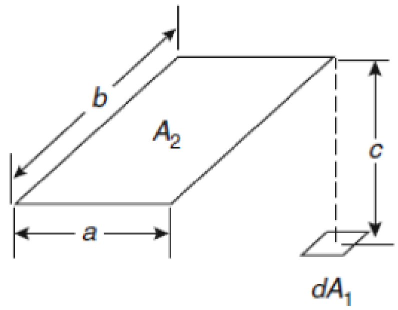


Figure C-27: View factor diagram.

It is assumed that the heat flux will be emitted from an entire glass curtain wall on an office level, which is 25 m wide and up to 3.1 m high:

- a = 3.1 m
- b = 25 m

The c length corresponds to the distance to the measured boundary. The curtain wall is located 3 m from side boundary

Table C-52: Emitted heat fluxes from.

Distance [m]	View factor	Heat flux [kW/m^2]	CV1 criteria [kW/m^2]	Pass/Fail
Boundary	0.179	24.05	80	P
1	0.153	20.48	40	P
3	0.114	15.28	20	P
6	0.080	10.71	10	P

C.4 FI1 – Fire Investigation

The intention of this design scenario is to allow for fire brigade intervention for the building. It is completed by determining the time required for the fire brigade to arrive curbside at the site of the fire, which is determined by using the Fire Brigade Intervention Model (FBIM) developed by the Australasian Fire Authorities Council (AFAC) [74]. Using the FBIM is a requirement of the Verification Method for this scenario.

C.4.1 FBIM Calculation

The methodology of the FBIM provides a line of flow charts that will describe each of the time components of the full fire brigade response time, including time to attack the fire. In this project, only the time from initiation to the fire brigade arrives at the site is considered so that the state of the building at the time of the fire brigade's arrival can be qualitatively assessed. For this purpose, four of the flow charts will be used within this section:

- Time taken for initial brigade notification;
- Time taken to dispatch resources;
- Time taken for firefighters to respond to dispatch call;
- Time taken to reach fire scene (curbside).

C.4.1.1 Chart 1 – Initial Brigade Notification

Table C-53 shows the first flow chart which is used to determine the time to brigade notification. It is assumed that the building has the longest alarm verification delay permitted by AS1670.1.

Item	Reference	Time [s]	Comment
Automatic detection	Yes	-	N/A
Suppression system	No	-	N/A
Time to verify fire	-	300	Assumed 5 minutes for occupants to become aware of fire incident.
Automatic connection to Fire Brigade	No	-	N/A
Telephone notification	Yes-	-	N/A
Time delay until notification of fire brigade	-	60	Assumed
Time to transmit information to Fire Brigade		**360**	**Sum**

Table C-53: Time taken for initial Brigade notification

C.4.1.2 Chart 2 – Dispatch Time

Table C-54 shows the time for the fire brigade service to dispatch services, which is based around the time for an emergency call center to receive the call, take down information and identify and dispatch the appropriate resources.

Item	Reference	Time [s]	Comment
Is the call via telephone, radio or passer by?	Yes	-	No active systems so assume fire brigade alerted by phone call.
Time to receive and take down verbal information	-	60	Assumed.
Call taken at central communications	Yes	-	Assumed.
Time to relay dispatch information by phone/radio (dispatch by phone/radio)	-	15	Assumed.
Tie for firefighters to respond to call and leave station	-	90	Assumed.
Time to respond		**165**	**Sum**

Table C-54: Dispatch time

C.4.1.3 Chart 3 – Time to Depart Station

The time taken for firefighters to respond to a call once dispatched is shown in Table C-55. The time is based on the building being in a Metropolitan Fire Brigade (MFB) area where the station is operated by career firefighters.

Item	Reference	Time [s]	Comment
Station manned full time	Yes	-	MFB Station
Firefighters in the fire station	Yes	-	MFB Station
Time to dress, assimilate information and leave station	-	90	Assumed
Time to respond & depart fire station		**90**	**Sum**

Table C-55: Time taken for firefighters to respond dispatch call

C.4.1.4 Chart 4 – Travel to site

Table C-56 shows the time taken from the fire brigade departing the fire station to arrival at curbside at the site.

Item	Reference	Time [s]	Comment
Percentile response time to be used	No	-	N/A
Turnout from fire station	Yes	-	N/A
Is the brigade emergency response route defined?	No	-	N/A
1.5 x Radial distance from fire station	-	4.5 km	Station is located 3 km from building
Design speed	Table F	44.3 km/hr	Major city inner suburg assumed
Is another appliance responding from another location?	No	-	N/A
Time to respond		**366**	**Sum**

Table C-56: Travel time

C.4.1.5 Total time to reach curbside

Based on the above FBIM assessment, the time taken from fire ignition to the arrival of the fire brigade at the curbside is 981 seconds (16.4 minutes).

C.4.1.6 Building Conditions at Arrival

The estimated time for the fire brigade's arrival to the site of the fire is 16.4 minutes based on the data provided in the previous tables. At this point, it would be expected for the fire to be fully developed. The building is not sprinkler protected, but compartmented by fire rated floors, so the brigade could expect to arrive at a building which had an entire story affected by fire. However, adjacent compartments and the staircase/elevator shafts could also be affected by smoke spread.

As this is a type A building, which is the most fire resistant type of buildings, the fire is not expected to spread vertically. Also, the loadbearing structures are not expected to collapse or undergo partial collapse due to failure during a fire event as the full burnout time exceeds the FRLs.

C.4.2 Facilities for the Fire Brigade Intervention

The following facilities for firefighting shall be provided:

- Fire Brigade external access;
- Tenability to enable identification and access to seat of fire;
- Fire hydrants internally and externally;
- Command and control provisions;
- Access to normally occupied areas for search and rescue.

Appendix D RSET Manual Calculations (Made by UQ)

RSET definition

RSET (Required Safe Egress Time) is the calculated time available between ignition of the design fire and the time when all the occupants in the specified room or location have left that room or location. RSET is determined using simple manual calculations.

$$RSET = \left(t_d + t_n + t_{pre}\right) + (t_{trav} + t_{flow})$$

where: t_d = detection time determined from deterministic modeling [s]

t_n =time for detection to notification of the occupants [s]

t_{pre} = time from notification until evacuation begins [s]

t_{trav} = time spent moving toward a place of safety [s]

t_{flow} = time spent in congestion controlled by flow characteristics [s]

Detection time

Where an automatic detection device is present, detection time is determined as the activation time of the device. The model used to calculate the detection time for an automatic occupant warning system uses an appropriate algorithm that includes at least a ceiling jet correlation or a CFD model code that solves for the velocity and temperature (and smoke/soot concentration) directly.

In the current building, smoke detection and alarm system (occupant Warning System) is installed. Heat detectors are installed in the car park level.

The detector criteria are summarized in the table below.

Heat detectors	**Spot/point smoke detectors (ionization and photoelectric)**
RTI = 30 $m^{½}s^{½}$ T_{act} = 57°C Radial distance = 4.2 m Distance below ceiling not less than 25 mm	Optical density at alarm = 0.14 m^{-1} Radial distance = 7 m Distance below ceiling not less than 25 mm

The detection time of smoke detectors and heat detectors is calculated using the zone model (CFAST software, version 7.2.1) described in Appendix B3.

Where there is no automatic detection device installed or an automatic detection failure is assumed, the occupants are assumed to be aware of the fire in the same room when the smoke is below 5% of the ceiling height.

Notification time
The notification time is assumed to be 30 seconds for type A occupants.

Pre-travel activity time
The pre-travel activity time is assumed to be 60 seconds for buildings where the occupants are awake, alert and familiar with the building (remote from the enclosure of origin).

Travel time
Travel time within a space is governed by:

a) the time taken to travel to an exit, or
b) the flow time (i.e. the time taken for all the occupants to flow through a restriction, typically a doorway, when queuing is necessary).

The greater of these two times is the evacuation time from the space.

Horizontal travel
For horizontal travel, the travel time is calculated based on the estimated travel speed. Horizontal travel speed is calculated using the following equation for type A occupants:

$$t_{trav} = \frac{L_{trav}}{S}$$

where: S = horizontal travel speed [m/s]

t_{trav} = travel time [s]

L_{trav} = maximum horizontal travel distance [m]

$$S = k - akD$$

where: D = occupant density of the space [persons/m^2]

k = 1.4 for horizontal travel

a = 0.266

Vertical travel

For vertical travel, the travel time is calculated based on the estimated travel speed. Vertical travel speed is calculated using the following equation for type A occupants:

$$t_{trav} = \frac{L_{trav}}{S}$$

where: S = vertical travel speed [m/s]

t_{trav} = travel time [sec]

L_{trav} = maximum vertical travel distance [m]

$$S = k - akD$$

where: D = occupant density of the space [persons/m^2]

k = 1.08 for vertical travel

a = 0.266

The value of k is calculated assuming the dimensions of stair riser and stair tread equal to 178 mm and 279 mm, respectively.

The maximum vertical travel distance (L_{trav}) is determined as the sum of the distance to be travelled along the stairs. According to the building specifications and drawings, the flight length is assumed to be 3.10 m, the landing length 1.20 m. Occupants need to cover 2 flights and 2 landings in order to descend 1 level.

Flow time

The flow time is calculated based on the estimated flow rate. Flow rate is calculated using the following equation:

$$F_c = (1 - ad)kDW_e$$

where: F_c = calculated flow [persons/s]

D = occupant density near flow constriction [1.9 persons/m^2 for doors]

W_e = effective width of the component being traversed [m]

k = 1.4 for horizontal travel

The effective width of the component being traversed (W_e) is calculated as the measured width minus the boundary layer. For doors, the boundary layer is equal to 0.15 m.

The maximum flow rate corresponds to a door of 0.95 m wide with a boundary layer each side of 0.15 m and a total effective width of 0.65 m for type A and type B occupants.

Sample calculation

Fire Scenario: *UT1: Fire in a storage room in a typical office level*

Detection time:	t_d = 25 s (from zone model)
Notification time:	t_n = 30 s
Pre-movement time:	t_{pre} = 60 s
Travel time (horizontal):	L_{trav} = 20 m D = 0.10 persons/m^2 $S = k - akD$ (S_{max} = 1.20 m/s) $S = 1.4 - 0.266 \cdot 1.4 \cdot D$ = 1.36 m/s $t_{trav} = L_{trav} / S$ = 20 / 1.20 = 17 s
Flow time:	N = 62 persons W_e = 0.75 m $F_c = (1 - aD)\ kDW_e$ F_c = (1 – 0.266 x 1.9) x 1.4 x 1.9 x 0.75 = 1 persons/s t_{flow} = N / F_c = 62 / 1 = 62 s
Evacuation time:	$t_{evac} = max(t_{trav}; t_{flow}) = t_{flow}$ = 62 s
Travel time (vertical):	L_{trav} = 0 m S = 0.95 m/s $t_{trav} = L_{trav} / S$ = 0 / 0.95 = 0 s
RSET:	RSET = $t_d + t_n + t_{pre} + t_{evac}$ = 177 s

Appendix E ASET Zone Model (Made by UQ)

ASET definition
ASET (Available Safe Egress Time) is defined as the time between ignition of the design fire and the time when the first tenability criterion is exceeded in a specified room within the building.

Zone model
The ASET is calculated using the zone model software CFAST, version 7.2.1. The assumptions of the model are described in section 6.1.1.2 and in the corresponding section of each fire scenario.

As defined by NCC 2019 Fire Safety Verification Method Section 3.6, The ASET tenability parameters measured at a height of 2.0 m above floor level, are:

a) An FED of thermal effects greater than 0.3.
b) Conditions where, due to smoke obscuration, visibility is less than 10 m except in rooms of less than 100 m2 where visibility may fall to 5 m.

These parameters are calculated as determined by ISO 13574:2012 Life-threatening components of fire – Guidelines for the estimation of time to compromised tenability on fires. The FED thermal tenability criteria is calculated as the time to experiencing pain due to convected heat accumulated per minute for fully clothed subjects:

$$t_{lconv} = (4.1 \times 10^8)T^{-3.61}$$

where: T = smoke temperature [°C]

The total fractional effective dose of heat acquired during an exposure can be calculated:

$$X_{FED} = \sum_{t_1}^{t_2} \frac{\Delta t}{t_{lconv}}$$

The visibility S due to smoke obscuration is calculated:

$$S = \frac{C}{kD}$$

where: C = aerosol mass concentration [3 for light-reflecting signs]

k = mass specific extinction coefficient [2.3]

D = optical density [m^{-1}]

Sample calculation

Fire Scenario: *CF 2 - Challenging fire in retail area*

Implementation of a zone model using the software CFAST, version 7.2.1. The geometry of the compartments and openings is modeled according to building specifications and drawings. Each compartment is modeled with adiabatic surfaces.

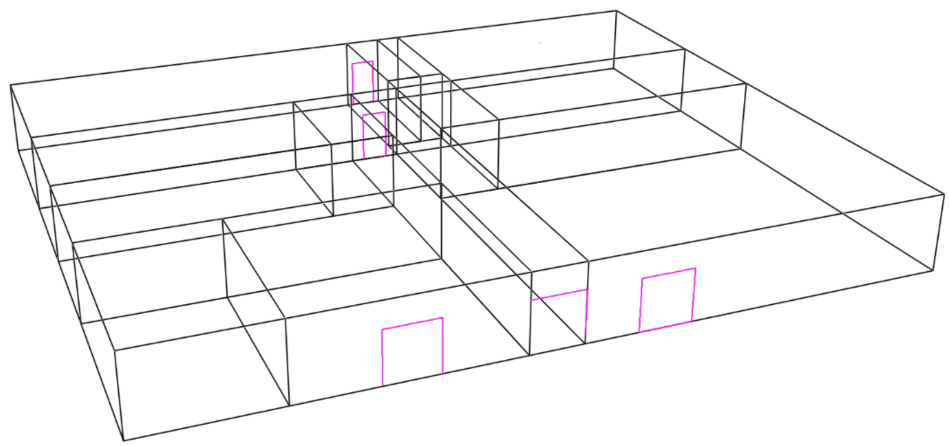


Figure E-1: CF 2 zone model geometry

A fire is placed in a specific compartment and position according to the fire scenario. For every fire scenario, the fire has the following characteristics:

- Fast t-squared fire ($\alpha = 0.047$ kW/s^2) up to flashover
- Peak Heat Release Rate (HRR) = 20 MW
- Soot Yield = 0.07 kg/kg (pre-flashover fire)
- Heat of Combustion = 20 MJ/kg
- Radiative Fraction = 0.35

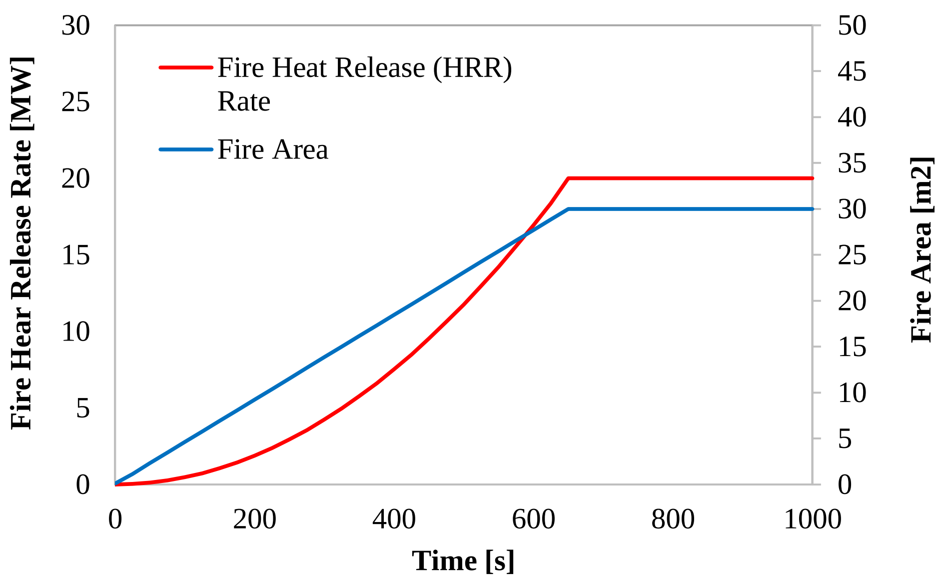


Figure E-2: CF 2 fire heat release rate (HRR) and fire area growth implementation into CFAST.

The surface area of the fire is modeled as a linearly increasing up to the peak heat release rate, from a minimum area (A_{min}) to a maximum area (A_{max}), defined according to the compartment dimensions. In the fire scenario CF 2, the fire burning area increases linearly from 0.09 m^2 (A_{min}) to 30 m^2 (A_{min}) up to the peak heat release rate (20 MW).

The model is run and the relevant results are collected and plotted.

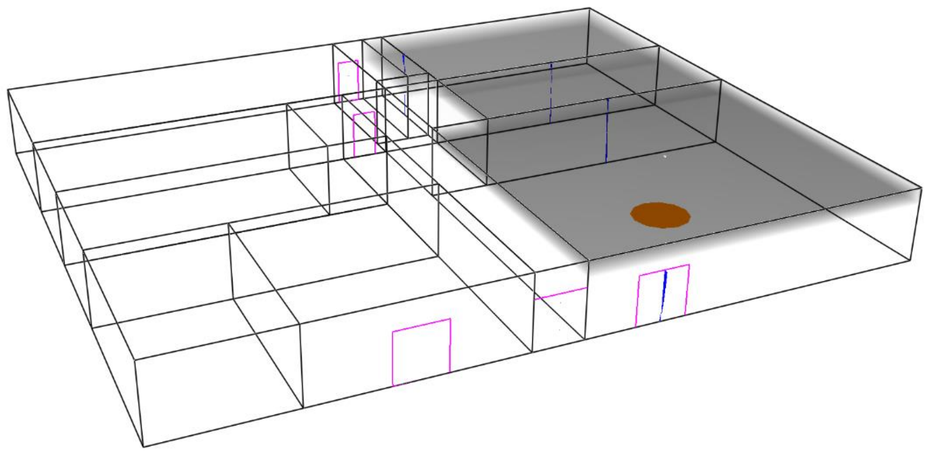


Figure E-3: CF 2 zone model at 95 s

As defined by NCC 2019 Fire Safety Verification Method Section 3.6, The ASET tenability parameters measured at a height of 2.0 m above floor level, are:

a) An FED of thermal effects greater than 0.3.
b) Conditions where, due to smoke obscuration, visibility is less than 10 m except in rooms of less than 100 m2 where visibility may fall to 5 m.

The FED thermal tenability criteria is calculated as the time to experiencing pain due to convected heat accumulated per minute for fully clothed subjects:

$$t_{lconv} = (4.1 \times 10^8) T^{-3.61}$$

where: T = smoke temperature [°C]

The total fractional effective dose of heat acquired during an exposure can be calculated:

$$X_{FED} = \sum_{t_1}^{t_2} \frac{\Delta t}{t_{lconv}}$$

The visibility S due to smoke obscuration is calculated:

$$S = \frac{C}{kD}$$

where: C = aerosol mass concentration [3 for light-reflecting signs]

k = mass specific extinction coefficient [2.3]

D = optical density [m^{-1}]

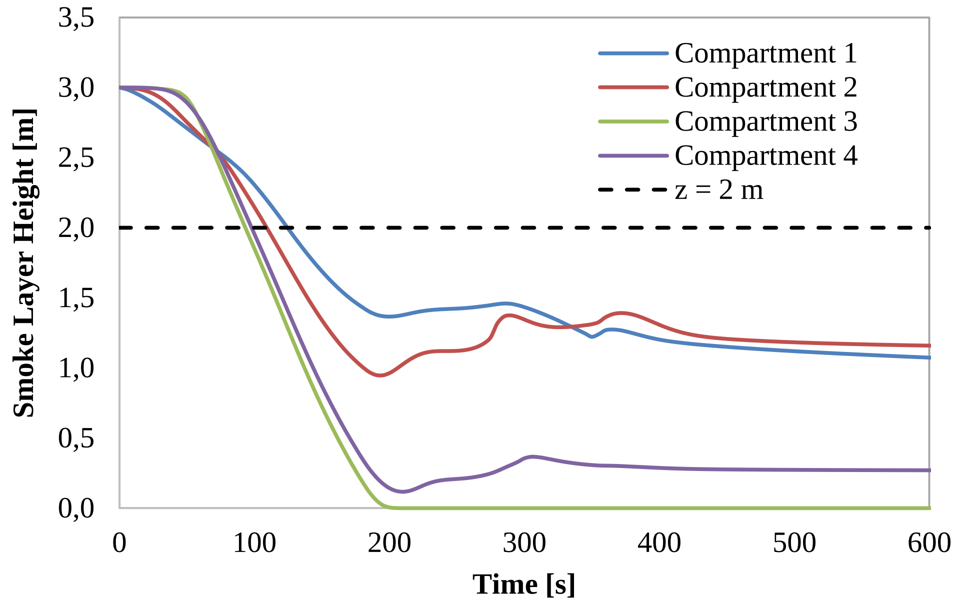


Figure E-4: CF 2 smoke layer height for different control volumes

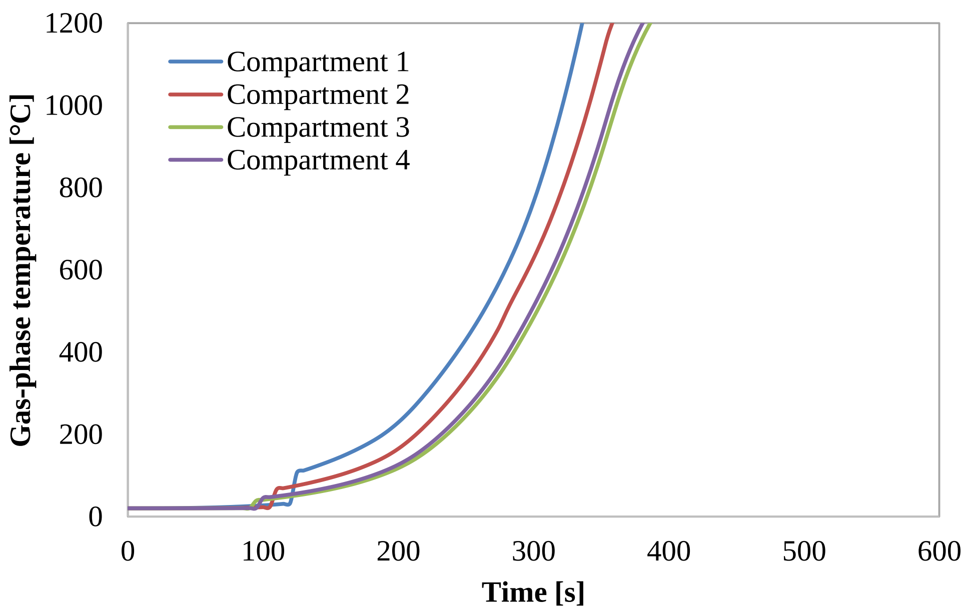


Figure E-5: CF 2 gas-phase temperature at 2 m above egress paths for different control volumes

Criteria	ASET time [s]
Time for smoke layer to descent to 5% of floor height	30
Time for smoke layer to descent to 2 m	95

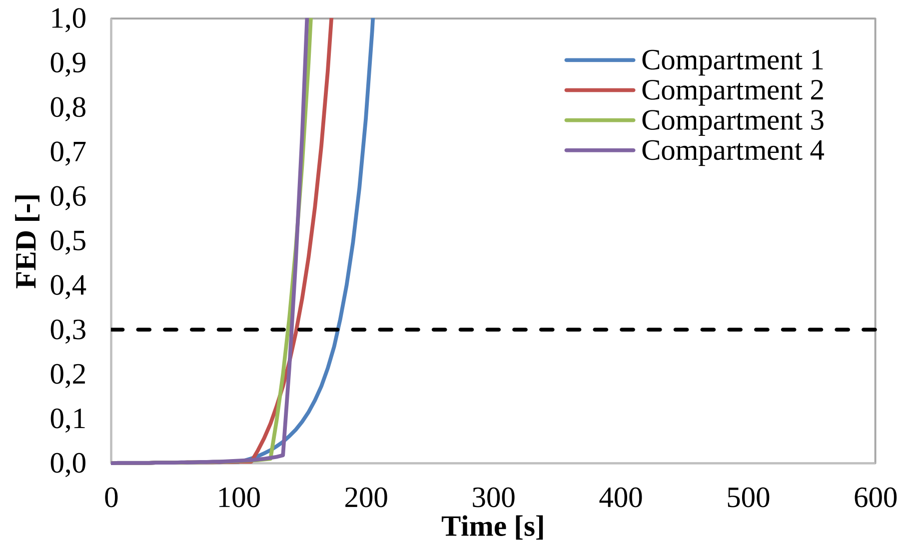


Figure E-6: CF 2 $FED_{thermal}$ at 2 m above egress paths for different control volumes

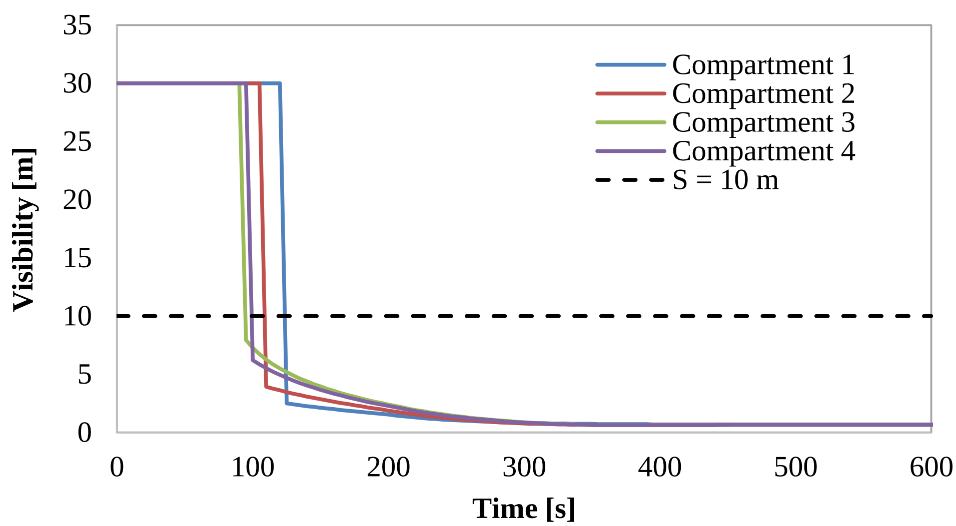


Figure E-7: CF 2 visibility at 2 m above egress paths for different control volumes

Criteria	ASET time [s]
Time for untenable conditions due to thermal effects (FED greater than 0.3)	140
Time for untenable conditions due to smoke obscuration (visibility less than 10 m)	95

Finally, the number of casualties can be evaluated starting from the following data and results for the *CF 2 fire scenario (Challenging fire in retail area)*.

- Occupancy = 120 persons
- RSET = 185 s
  - Detection time = 35 s
  - Notification time = 30 s
  - Pre-movement time = 60 s
  - Evacuation time (flow time) = 60 s
- ASET = 95 s
  (Time for untenable conditions due to smoke obscuration (visibility less than 10 m)

According to the previous assumptions and results, when the fire compartment reaches untenable conditions due to smoke obscuration (95 sec), the retail area occupants have not started flowing through the exit doors yet (starting from 125 s).

Therefore, in this fire scenario, all the occupants are injured due to untenable conditions. The total number of casualties is equal to the total number of occupant (120).

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