OPTIMIZATION OF THE ELIMINATION OF DEAD ZONES, AND AIR QUALITY ANALYSIS AT LOCAL MEAN AGE OF AIR IN AN UNDERGROUND CAR PARK WITH AN IMPULSE VENTILATION SYSTEM

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Optimization, of the Elimination of Dead Zones, and Air Quality Analysis at Local Mean Age of Air in an Underground Car Park with an Impulse Ventilation System

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as University Supervisors.

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DEDICATION

To God Almighty, my creator, my strong pillar, my source of inspiration, wisdom, knowledge, and understanding.

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ABBREVIATIONS AND ACRONYMS

ACH	Air Changes per Hour
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BOCA	Building Officials and Code Administrators
BRE	Building Research Establishment
BS	British Standards
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institute of Building Services Engineers
CO	Carbon Monoxide
DR	Drive Way
EA	Exhaust Air Point
EM	Emergency Mode
FA	Fresh Air point
HRR	Heat Release Rate
IAQ	Indoor Air Quality
IVS	Impulse Ventilation Systems
LMA	Local Mean Age of Air
MAA	Mean Age of Air
NFPA	National Fire Protection Authority
NPV	Normal Pollution Ventilation
SHC	Smoke and Heat Control
S & P	Sola and Palau
UK	United Kingdom

LIST OF SYMBOLS

Symbol	**Description**
A	Surface Area of the Car park [m^2]
COppm	Carbon Monoxide Concentration in Part per Million [ppm] :
Dm	Internal Diameter [mm]
Fth	Thrust [N]
H	Floor to Ceiling Height of the Car Park [m]
L	Effective Length of the Car Park [m]
Q	Airflow Rate [m^3/hr]
T	Temperature in [$^{\circ}$C]
N	Torque [Nm]
v	Velocity of Air [m/s]
V	Volume of the Car Park [m^3]
W	Effective Width of the Car Park [m]

ABSTRACT

It is important to provide efficient ventilation of harmful gases from car engines to meet set thresholds for international air quality in covered car parks. Efficient ventilation is also crucial in case of fire as it serves to dilute the released smoke; thus preventing suffocation. In trying to overcome these challenges of ductless systems, researchers have introduced the Impulse Ventilation System (IVS) which uses jet fans for mixing and dilution of toxic exhaust gases. Most researchers have assumed that car park soffits are entirely flat despite services such as beams, sprinklers among others, resulting in very low headroom making it impractical to run jet fans below the beams. The jet fans can only be installed in the flat soffit whereby the beams block easy airflow resulting in dead zones and failing to achieve the recommended car park air quality. Moreover, these causes resistance and turbulence hence stagnating the air making the required air velocity of local mean age (LMA) of 0.1 m/s and above the 1.7 m LMA height (average human height) not achievable. This research is aimed at addressing the above challenges by using computational fluid dynamics (CFD) techniques in designing an IVS for a covered car park. The study also sought to eliminate dead zones and ensure desirable velocity of 0.1 m/s or greater at LMA at 1.7 m plane hence better air quality by optimally positioning economical jet fans for efficient operation for both the normal pollution ventilation (NPV) and emergency Mode (EM). A case study used in this study is Konza Technopolis, in Kenya (1.689°S 37.185°E). The optimal placement of jet fans had 20% reduction on the number of jet fans from 26 to 21 hence a potential of monetary savings compared to the conventional method. The research results showed that there was an effect on the velocity obstruction on the jet fans that are in close proximity to the down stand beams. Three validation experiments were done; dead zones elimination was done by conducting experimental measurement points after driving a group of cars. Other validation experiments were conducted on analysis of airflow of entire car park and velocity at LMA at 1.7 m plane results analysis. The methodology used has the potential to reduce dead zones and increase air quality by 99%. From validation experiments, it was conclusive that the research was successful as all stagnant air were eliminated and desirable velocity range of 0.1 m/s and above achieved LMA at 1.7 m plane achieved. This research can be used to improve the design of ventilation systems while cutting down on time, cost and increasing efficiency while working with design standards.

CHAPTER ONE

INTRODUCTION

1.1 Background

Automobile parking lots/garages are either partially open or fully enclosed. Partially open parking garages are typically above-grade with open sides and hence don't require mechanical ventilation. Fully enclosed parking garages are sometimes underground and require mechani-cal ventilation due to two main reasons. First, is the extraction of harmful gases from vehicle emissions hence controlling pollution. Exhaust gases are primarily carbon monoxide (CO), nitrogen oxides (NOx), and sulphur oxides (SOx) which cause poor air quality in an under-ground car park (Bacak, 2017; Spiljar, Schneider & Drakulic, 2018). Air quality is maintained at acceptable levels through air replacement at intervals. This mode is referred to as Normal Pollution Ventilation Mode (NPV). Second, mechanical ventilation is used for smoke extraction in case of fire. During fire breakout, the toxic gases emitted spread faster than the fire and may be a secondary source of fatalities. These gases, need to be evacuated fast in the occurrence of a fire. This mode is referred to as Emergency Mode (EM).

There are international design standards for ventilation requirements of enclosed parking garages as presented in Table 1.1. The two major international standards for ventilation requirements are the American Society of Heating, Refrigerating and Air Conditioning Engi-neers (ASHRAE) and the British Standard (UK). For the enclosed parking facilities ac-cording to ASHRAE, (Table 1.1), the ventilation for acceptable indoor air quality specifies a fixed ventilation rate of below 7.62 L/sm^2($1.5\ cfm/ft^2$) of gross floor area. This is within an average period of 1 hour and 8 hours, where the maximum carbon monoxide exposure should be 35 ppm and 9 ppm, respectively. The ventilation flow in terms of air changes per hour (ACH) required for garages therefore will depend on the floor area of the car park. For the UK standard, the minimum air changes per hour are 6 ACH and 10 ACH for the NPV and EM modes respectively, irrespective of a car park area, making them more stringent.

Table 1.1: Summary of Major International Design Standards for Ventilation. (Krarti & Ayari, 2003)

Code	Time (hrs)	CO (ppm)	Ventilation
ASHRAE	8	9	7.6 l/s.m2
	1	35	[1.5 cfm/ft2]
BOCA	-	-	6 ACH
FRANCE	Ceiling	200	165 l/s.car
	20 minutes	100	[350 cfm/car]
JAPAN	-	-	6.35 – 7.62 l/s.m2 1.25 – 1.5 cfm/ft2
NFPA	-	-	6 ACH
OSHA	8	36	-
	max	200	-
UK	8	50	6-10 ACH
	15 minutes	300	

With an average period of 8 hours and 15 min, the maximum carbon monoxide exposure recommended should be 50 ppm and 300 ppm, respectively. This means that the average recording of carbon monoxide during NPV mode in 8 hrs should not exceed 50 ppm whereas during EM mode within 15 minutes the CO concentration shouldn't exceed 300 ppm (British Standards Institution, 2013). The UK standard will be adopted as since it is more stringent compared to ASHRAE and gives the acceptable carbon monoxide concentration (CO) (Kavanaugh & Rafferty, 2015; British Standards Institution, 2013). According to (Kavanaugh & Rafferty, 2015; British Standards Institution, 2013), the following are the main car park ventilation systems design end goals:

1. Basement or enclosed car park storeys, mechanical ventilation should be provided to at least 6 air changes per hour,
2. Assist fire-fighters by providing ventilation to allow faster clearance of the smoke once the fire has been extinguished,
3. Help reduce the smoke density and temperature during the course of fire.

For many years, ducted systems or convectional systems have been widely used for ventilation worldwide. This entails the air being drawn through fans and ducts with diffusers, grills, and nozzles (Figure 1.1). This is done for both the fresh air replacement and discharged air. To avoid pressure drop, airflow is kept as low as possible (Senveli et al., 2015).

Ducted systems have several challenges such as limitation on emergency mode operation and has high operation and investment costs. Apart from the high initial cost for these conventional systems, loss of property and death through fires as well as respiratory issues are some of the challenges encountered when using such a system. Additionally, they also take up a lot of space. These systems are also complicated as beam penetration is required after installation. High ceiling height is also required on the design and it's difficult to zone.

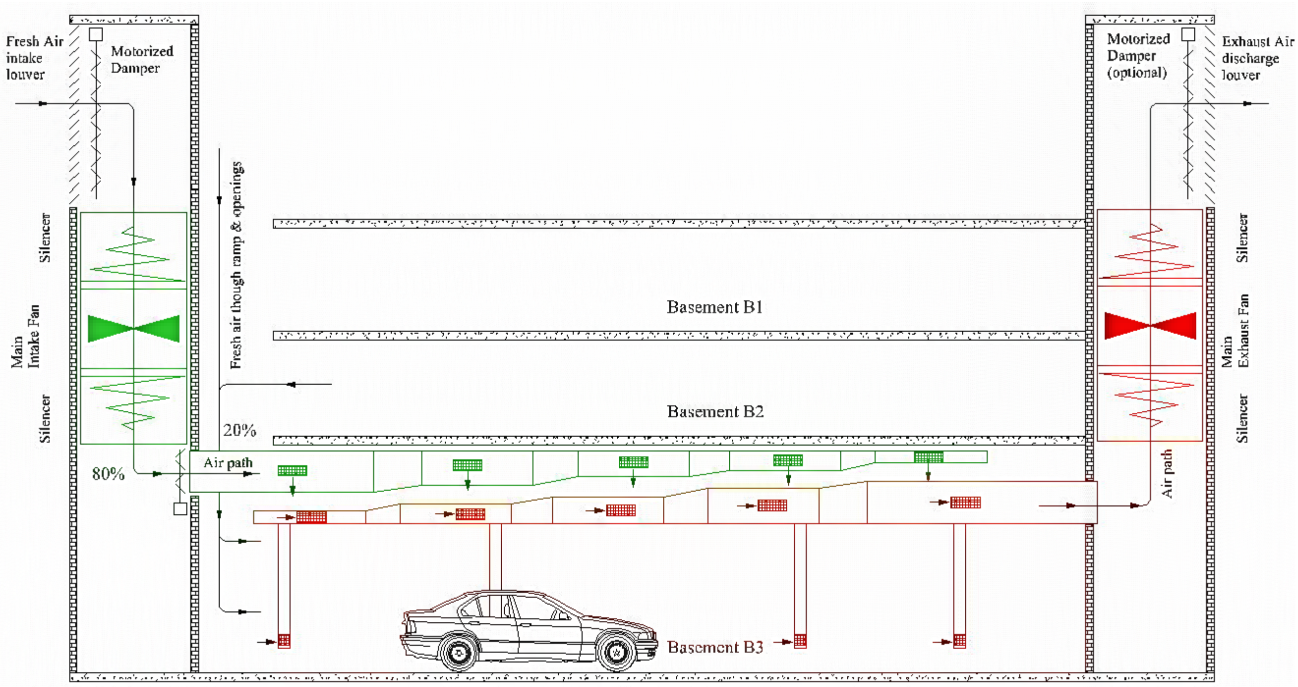


Figure 1.1: Conventional car park ventilation (Ducted System). (Kruger, 2018)

The most recent ventilation development is the IVS as shown in Figure 1.2. Air is transferred through jet vent fans without air ducts. Axial ventilators (jet fans) are suspended under the car park ceiling to generate the momentum necessary to promote the internal ventilation airflow. The jet fans provide elimination of air distribution within the car parks as well as reduction of supply of exhaust air as they dilute harmful gases. Jet fans operate on well proven longitudinal tunnel ventilation principles producing a high velocity jet of air, in turn moving a larger quantity of air surrounding the fan through a process known as entrainment (Celen et al., 2014). The increase of discharge by a fan results in the increase of the amount of air entrained by a single fan consequently resulting in an increase in velocity.

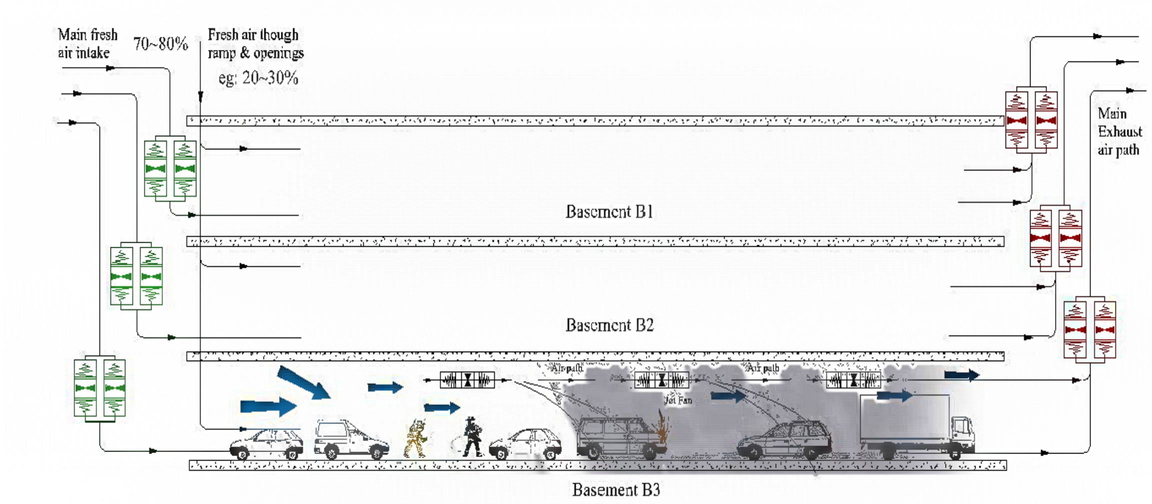


Figure 1.2: A complete impulse ductless system. (Kruger, 2018)

These characteristics directly relate to the thrust rating of the fan; which is measured in Newtons (N). This driving force or impulse force is the product of the mass flow r ate and the change in velocity contrary to conventional fans where output is measured in volume flow [m^3/hr] and pressure [Pa]. Different speeds can be achieved in particular sections depending on the size of the system.

Most researchers have made the assumption that car parks are entirely flat whereas other installations such as sprinklers cause a very low headroom. Most of these designs become impractical as the fans have to be installed below the beams or sometimes in the beam pockets. This causes resistance and turbulence resulting in dead zones which lead to the non-achievement of the desired air quality. Dead zones cause the impulse ventilation systems to be inefficient where functionality needs arise.

1.2 Statement of the Problem

Conventional ducted ventilation systems and accessories have high capital costs and increase in friction loss and system resistance. Ducts cause stagnated zones and high pollution levels in normal mode and smoke concentration in fire mode a dead zones. Ducted systems are bulky, non aesthetic, not flexible and have a lot of waste in case of design changes and in case of alterations and renovations. Fire escape, rescue, and zoning operations are difficult to operate due to stagnated zones in car park areas in case of heavy smoke operation. The most recent impulse ventilation systems have tried to address these issues by being sizable, and compact, aesthetic, flexible and easy in design.

They can easily accommodate alterations and ease to operate during fire m ode. A practical car park has other design challenges requirements considerations. These include structural down-stand beams, as well other services such as sprinklers or rather too low headroom due to economic constrains of client requirements. This causes resistance to airflow and turbulence; hence, dead zones and air quality at 1.7 m LMA height not being achieved. Dead zones cause the impulse ventilation systems not to function when operation need arises. Apart from these, convectional systems require higher initial costs with their system failure to operate during fire mode can lead to losses of property to fire and death or health problems to human beings. Consequently, this research focuses on optimization and elimination of dead zones of design on car park ventilation due to obstructions problems and 1.7 m air quality LMA height using CFD. Emerging smart cities such as Konza Technology city where this case study have been conducted (1.689°S 37.185°E) in Kenya will require to achieve or surpass green global standards on air quality where each system depends on the underground car park architecture.

1.3 Objectives

1.3.1 Main Objective

The main objective of this research is to analyse the effect of obstructions and air quality desirable velocity of 0.1 m/s at 1.7 m Local Mean of Air height in an impulse ventilation system by using computational fluid dynamics for pollution and smoke control in underground car park design.

1.3.2 Specific Objectives

1. To indentify dead zones using computational fluid dynamics (CFD) model of an IVS car park with conventionally placed jet fans.
2. To optimally place jet fans in an IVS car park to eliminate dead zones for improvement of air quality.
3. To conduct, and analyze the validation experiments of the optimally placed jet fans in the car park.
4. To analyse air quality desirable velocity of 0.1 m/s of the optimized placement in relation to dead zones elimination and Local Mean Age of air at 1.7 m height for both Normal Pollution Ventilation and Emergency Mode.

1.4 Justification

As the global population is increasing, the number of cars are increasing. Parking spaces are decreasing and thus more need of multi-storey underground car parks. Moreover, with the rapidly emerging smart cities like Konza Technopolis there is need to achive global standards on air quality and safe evacuation in case of fire. Without a proper CFD analyses during design, standard design objectives can hardly be achieved. Therefore, notwithstanding short-comings such as obstruction in implementation of ventilation's designs, there is urgency to ensure accuracy on design. With proper CFD on car park architecture, functionality will be guaranteed when need comes, hence confidence in operation of these systems.

CHAPTER TWO

LITERATURE REVIEW

2.1 Ventilation Systems Overview

Ducted systems entail the air being drawn through fans and ducts with diffusers, grills and nozzles. Ducted systems have a number of challenges such as limitation on emergency mode operation as well as high operation and investment costs. Besides, it also takes up a lot of space as analysed by (Senveli et al. 2015). This system is also complicated as beam penetration is required. High ceiling height is required as well, and it is difficult to zone out areas on the control system. These challenges have led to the invention of Impulse ventilation system (Kruger 2018). Impulse ventilation system systems is where air is transferred through jet vent fans without air ducts. Axial ventilators (jet fans) are suspended under the car park ceiling. Jet fans generate the momentum necessary to promote the internal ventilation airflow. The jet fans provide elimination of air distribution within the car parks as well as reduction of supply and exhaust air as they dilute harmful gases. Most of the research globally has made the assumption that car parks are entirely flat whereas in a car park presence of the services such as sprinklers result to a very low headroom. Most of these designs become impractical as the fans have to be installed below the beams or sometimes in the beam pockets. The resistance and turbulence results in dead zones hence the non-achievement of the desirable air quality (Alainto et al., 2017).

2.1.1 Conventional Systems

From Figure 2.1, it is clear that air passes through duct, fans, along with diffusers, grills, and nozzle. These conventional systems (Ducted systems)systems also contain supply and exhaust air fan depending on architecture. This is performed for both the fresh air and the discharged used air. The airflow rate is kept as low as possible to prevent pressure drop. However, this means that the channels should be relatively wide, and therefore requires a larger area. It is a challenge on the emergency mode operation and has high operation and investment costs. They also take a lot of space. They are complicated as beam penetration is required. High ceiling height is required as well on the design and it is difficult to zone areas on control system. Due these challenges this has led to the invention of IVS Systems.

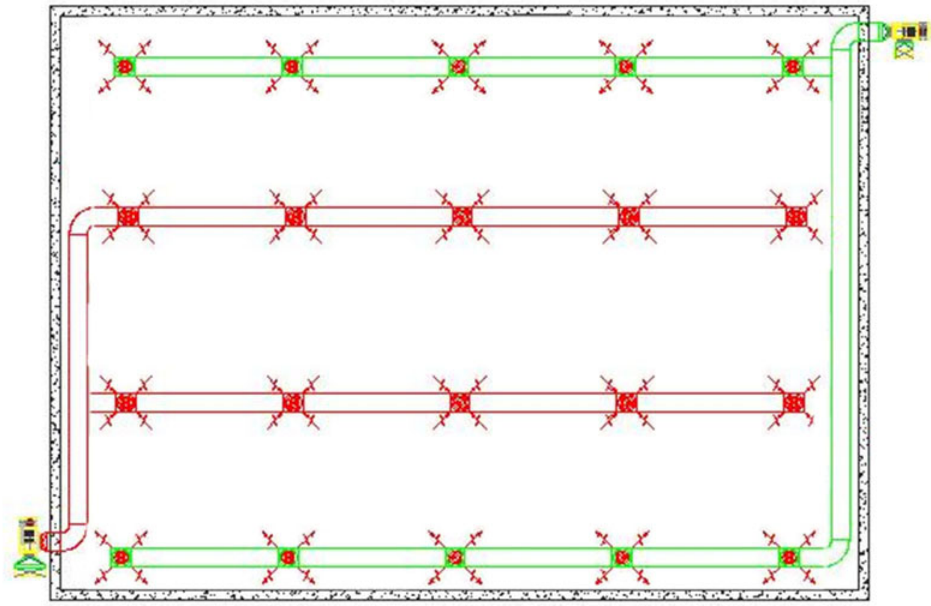


Figure 2.1: Convectional ventilation (Ducted systems)

2.1.2 Impulse Ventilation Systems

This is a ventilation system that is based on the utilization of induced jet fans. The air in one region is transported through a long distance by the induction of the air through the fan units in a series mode (Calen et al., 2014). Optimal arrangement of fans to provide good ventilation, affects allocated number of units and the volume flow rate of each of these units. Flow barriers and obstacles in an architectural facility such as pillars and beams affect the air flow of these system. Such an arrangement is dependent on the structural configuration of the building.

A jet vent fan normally induces air stream to the exhaust outlet points resulting in air move-ment to the surrounding shadowy area to the main air stream. The system equally disperses fresh air throughout the coverage area, thus diluting the congested and contaminated air by stirring it with fresh air and induces air stream to the outlet. Induction effect from pressure difference creates a whirling effect.

From Figure 2.2, it is clear that the difference with a ducted system is that air is trans-ferred by jet vent fans and no ducts containment which is a direct transfer (induction). The main extraction shafts can be either masonry or ducted, but masonry is preferred due to less friction/pressure drop. Figure 2.3 shows the initial rule of thumb guide for the jet fans place-ment in an underground car park. The jet fans should be spaced not more than 15 m apart sideways and not more than 30 m apart for air-throw distance (Kruger, 2018).

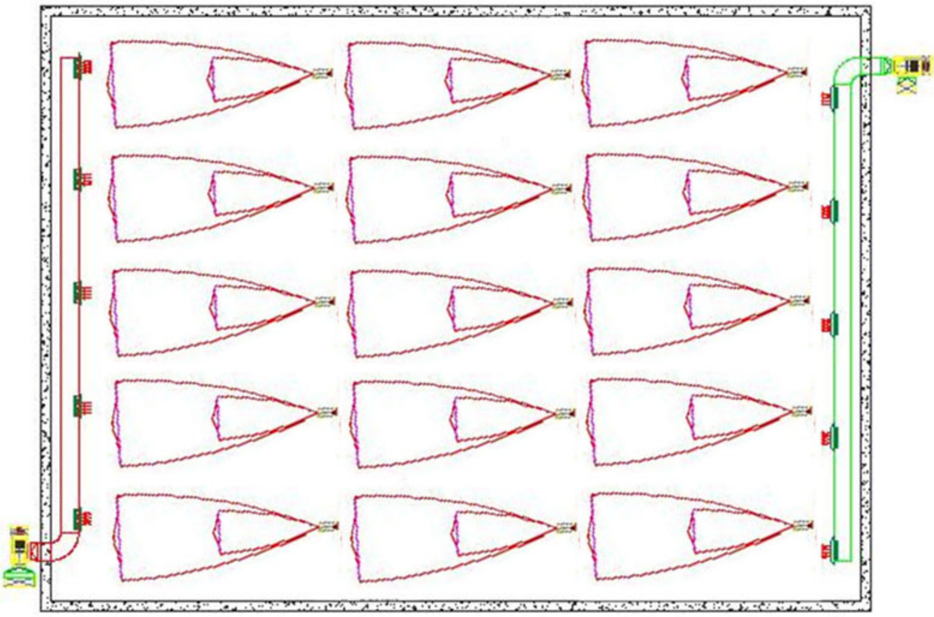


Figure 2.2: Impulse ventilation with ducted system

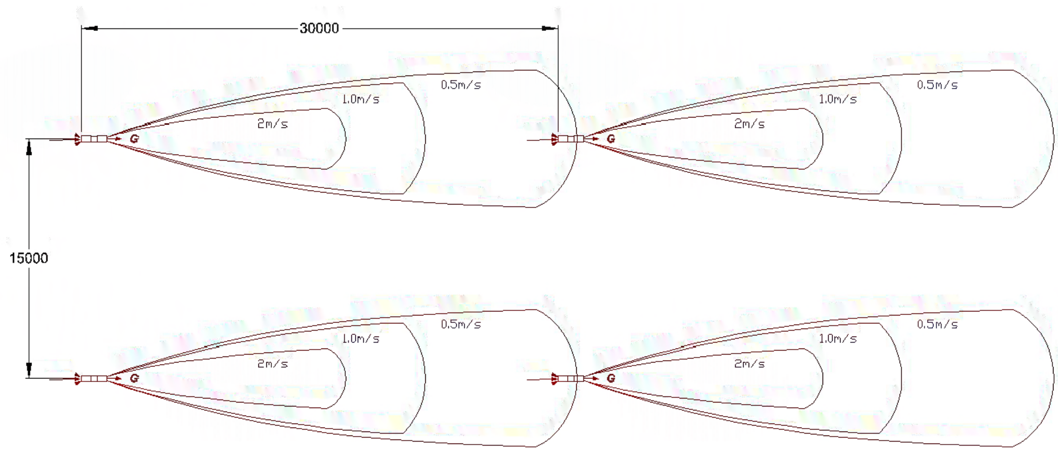


Figure 2.3: Jet fans rule of thumbs placement. (Kruger, 2018)

2.1.3 Jet Fans Air Throw and Coverage Area

Figures 2.4 and 2.5 show a chart for determining centreline velocities of axial and radial jet and the throw of a free air jet. Horizontal or vertical axial distance is the distance an air stream travels after leaving an air outlet before maximum stream velocity is reduced to a specified terminal velocity. Maximum throw [T_X] (Kruger, 2018). The distance from the outlet to where the centreline velocity is 0.25 m/s is defined as;

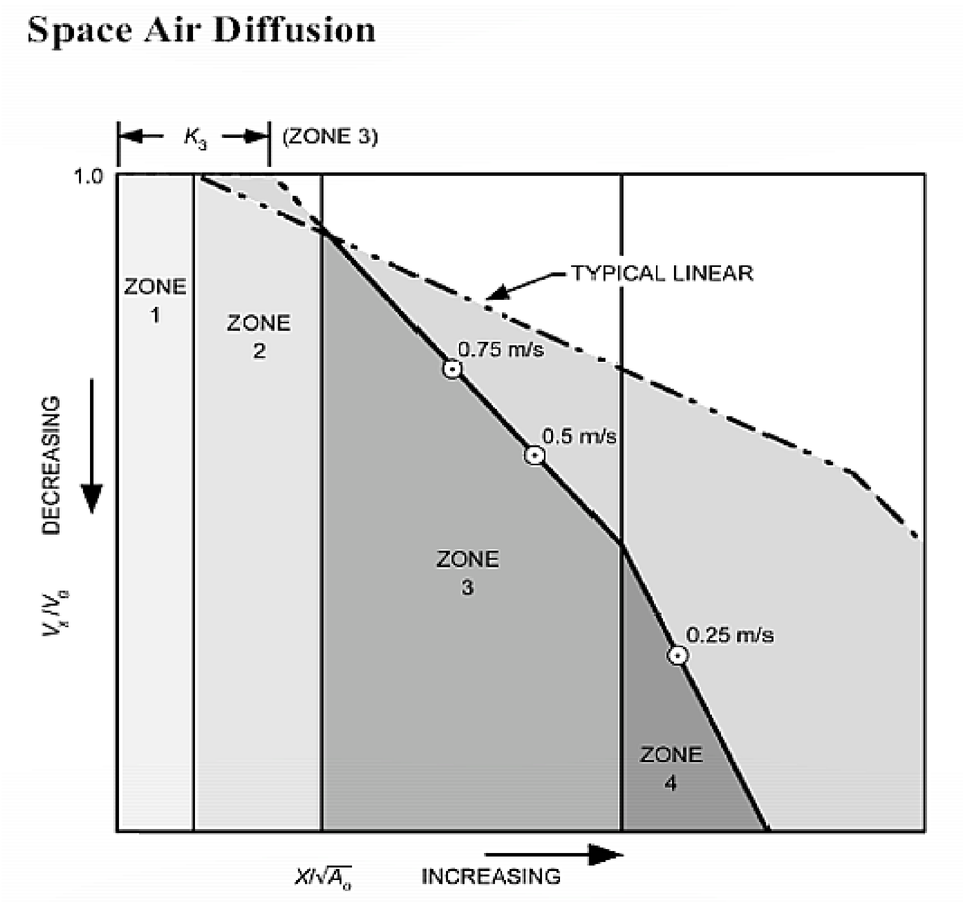


Figure 2.4: Space air diffusion centreline velocities of the free air jet of a jet fan. (Kruger, 2018)

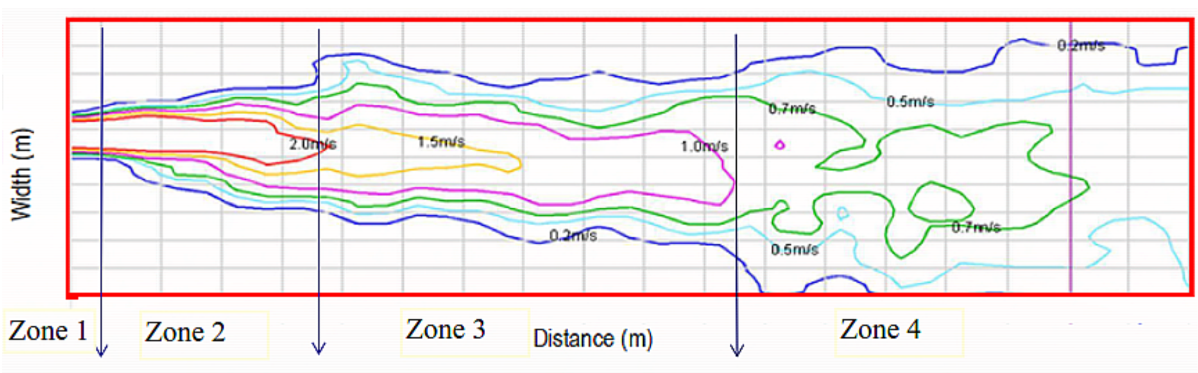


Figure 2.5: Throw of free air jet at centreline velocities of a jet fan. (Kruger, 2018)

$$T_x = \frac{1.33K_cQ_o}{V_x\sqrt{A_0}} \tag{2.1}$$

Where K_c, centreline velocity constant, Q_o is the discharge from outlet of a jet fan, V_x is centreline velocity at distance x from outlet [m/s], x is distance from outlet to measurement of centreline velocity V_x (m), A_o is core area of neck area in m^2 and as shown in free flow air throw as shown in Figure 2.4.

The area of coverage by single jet fan is given by the Equation 2.2, below;

$$A_x = \frac{K_c \times D_n \times V_a}{V_t}. \qquad (2.2)$$

Where A_x is the area, K_c = 5 (a constant), D_n is the diameter of the nozzle, V_a is the velocity of air stream and V_t is the velocity of throw point.

2.2 Car Park Ventilation Design Standards

There are two main design approaches mostly considered in the United Kingdom (UK); Building Research Establishment (BRE) approach, which considers that fire will occur only on the most probable area (Probabilistic fire scenarios) while also considering the plume ranges. The other approach, British Standards, on the other hand, considers the occurrence of fire anywhere in the car park. As stated earlier in Chapter 1, on introduction, the UK standard was adopted as it is more stringent compared to national fire protection authority and gives the acceptable carbon monoxide concentration levels.

Ventilation in enclosed underground spaces presents many concerns (Kavanaugh & Rafferty, 2015) recommends that a flat ventilation rate of 0.0075 m3/(s.m2) equal to 6 ACH is used for enclosed parking garages. The use of mechanical intake fans can cause problems with mechanical extraction. Because the exhaust air that is extracted has a greater volume than the inlet air. As the fire grows and declines, there is mismatch in volume between the inlet air and the extracted warm air. A moving air stream that has a lower pressure than the still air will attract the stationary air toward itself. The force of attraction increases as the velocity of the air stream increases. Consequently, the system should be designed to run in two parts; with the most common approach involving each part suggested that each part arranged so that 50 % of the outlets are at high levels and 50 % are at low levels, according to many smoke ventilation codes (CIBSE, 2018).

2.2.1 UK Standard

The standard considers the extraction for NPV to be 6 ACH and 10 ACH for EM mode (British Standards Institution, 2015). It gives the acceptable levels of ACH but does not provide a solution to dead zones elimination in a car park, 3D surface CAD modelling development and associated challenges.

British standard gives the acceptable levels of ACH, but it does not provide solution to dead zones elimination in a car park. (Bulacu et al.,2018; Jug, Petelin, & Bukovec, 2011; Khalil, & Gomaa, 2017) analysed underground car park on probabilistic basis. CFD simulation were done using Fire Dynamics Simulator, a and ANSYS FLUENT® software CFD tools. The consideration of the fire zone was also studied. The underground car park used in this study was 5, 290 m^2 in area with a height of 3.7 m. A comparison between CFD results and analytical correlations for the fire modeling was made. The ANSYS FLUENT® software was used for all simulations. Though the CFD simulations were done by programmes to achieve the UK stardard, a solution was not devised for CFD analysis to address dead zones on the entire car park and LMA.

2.2.2 National Fire Protection Authority

The National fire protection authority (National Fire Protection Association, 2021) standard regards enclosed vehicular facil-ities design criteria to be as per ASHRAE application. The standard for basement parking load ventilation calculation was based on;

1. Basement car parking for allowable carbon monoxide (CO) levels.
2. Basement car parking for average entrance and exit times for vehicles.
3. Basement exhaust air rates for car parking.
4. Fresh air ventilation for basement parking.

The following information is used to determine the designed airflow rate required to ventilate an enclosed parking garage.

1. Number of cars in operation during peak hours (N).
2. Average CO emission rate for a typical car (E), lb/h.
3. Average length of operation and travel time for typical car (0),s.
4. Acceptable CO concentration in the garage (CO max), ppm.
5. Total floor area of parking facility (Af), ft2.

2.2.3 Probabilistic Fire Scenarios

Probabilistic fire scenarios is Building Research Establishment (BRE) standard approach which considers fire will only occur on the most probable area. The plume general areas range from 2×2 m to 4×4 m depending on the risk and terms of occupation of the building.

2.2.3 Probabilistic Fire Scenarios

From heat release rate, the total extraction flow rate is entrained to be approximately 4 MW (Xu et al., 2018; Harrison, & Spearpoint, 2006). The standard has low flow rate hence, few main extraction fans thus making it economical.

(Jug, Petelin, & Bukovec, 2011) studied the correlation between underground car park impulse ventilation control and realistic fire scenarios. The basic geometry was simulated in a space 40 m long, 35 m wide and 2.4 m high. Twelve jet fans were placed at the ceiling. Each fire scenario included same fire load of of approximately 4 MW. The CFD code was validated using an Alpert correlation; and no simulations were done for the calculations of the temperature and velocity field of an unconfined ceiling jet from a turbulent fire plume.

$$\frac{T_{max} - T_{\infty}}{T_{\infty}} = 6.18 * Q_h^{\frac{2}{3}} \ , \ \frac{r}{h} \leq 0.18 \qquad (2.3)$$

$$\frac{T_{max} - T_{\infty}}{T_{\infty}} = 1.97 \left[\frac{*Q}{}h\frac{r}{h}\right]^{\frac{2}{3}} \ , \ \frac{r}{h} \leq 0.18 \qquad (2.4)$$

$$*Q_h = \frac{Q}{(\rho)(C_p)(T_{\infty})(\sqrt{gh})(h^2)} \qquad (2.5)$$

In the equations [2.3 – 2.5] $_{max}$ is the ceiling temperature, T_{∞} is the ambient temperature and $*Q_h$ is non-dimensional heat release.

The cold test results were compared with calculations and some similarity was seen. It was expected that cold smoke developed in a different way than a real hot smoke, produced from car combustion. The author did not address a solution analysis to address dead zones on entire car park in relations to obstructions and LMA at 1.7 m height.

Cold test results were compared with calculations and some similarities were observed. The expectation was that the cold smoke would have developed in a manner different to the real hot smoke produced by the combustion of a car. The research did not address a solution targeting dead zones on the entire car park in relation to obstruction.

According to Table 2.1, it is seen that the occurrence area of fire for an indoor car park with a sprinkler system would be 2 m × 5 m; which is the dimension of the car with a total heat release rate of 4 MW. These parameters would be useful in the calculation of smoke control in a car park.

Table 2.1: Steady-state Design of Fire. (Hidalgo et al., 2019)

Fire Parameters	Indoor Car park with-out Sprinkler system	Indoor Car park with Sprinkler system
Dimensions	5 m × 5 m	2 m × 5 m
Perimeter	20 m	14 m
Heat Release rate	8 Mw	4 Mw

2.3 Local Mean Age of Air

When the air quality in an underground car park is considered as Local mean age of Air (LMA) is one of the most important parameters. The LMA is the average time for the air to reach the arbitrary point of the underground car park from the main air entry point in an underground car park. The concept of LMA helps re-position and determine the optimal number of jet fans. Increasing the number of jet fans does not improve mechanical ventilation system efficiency. Additional focus is on the validity of the choice of the jet fan ventilation system for the underground car parks.

The most appropriate results for analysing the airflow are air velocities and LMA. In the LMA analysis no re-circulation is desired in any of the zones. The desired parameter for LMA for NPV analysis is 950 seconds. Again for the LMA, this parameter is 360 seconds (approximately 10 ACH) in the EM mode (Alianto et al., 2017). One of the most important results to be examined in terms of NPV analysis, the LMA (Local Mean Age), that is the average period of time for air particles to stay in the environment. This is because; the purpose in NPV ventilation is to discharge CO particles at certain time intervals. The results were acceptable, since the LMA values are in the desired range of 280 and 900 seconds for both NPV and EM modes respectively.

2.4 Computational Fluid Dynamics

Computational fluid dynamics is a science that works with use of digital computers, producing quantitative predictions of fluid-flow phenomena based on the conservation laws (conservation of mass, momentum, and energy) governing fluid motion. For CFD software analysis, fluid flow and its associated physical properties, including velocity, pressure, viscosity, den-sity, and temperature, are calculated based on defined operating conditions. Most CFD tools are based on the Navier-Stokes (N-S) equations. These tools helps in identification and analyses of dead zones resulting ultimately to better performing and more efficient final system.

2.4.1 Governing and Solver equations

The structure of thermo-fluids examination guided by governing equations that are based on the conservation law of fluid's physical properties. The equations are laws of conservation as follows:

1. Conservation of Mass: Continuity Equation.
2. Conservation of Momentum: Newton's Second Law.
3. Conservation of Energy: First Law of Thermodynamics or Energy Equation.

These principles state that mass, momentum, and energy are stable constants within a closed system therefore everything must be conserved.

(Tilley, Deckers & Merci, 2012) studied the computational fluid dynamics (CFD) relationship between venti-lation velocity and smoke back layering distance in large closed car parks. They used a large set of (more than 350 zones) CFD simulations as numerical experiments from parameter variation in the simulations. They recommended the key formulas for critical inlet velocity, the difference between inlet and outlet velocity and the required ventilation velocity in the car park. However, the study did not consider jet throw on obstructions and their dead zones effect.

(Deckers et al., 2013) performed CFD simulation for full-scale car park fire experiments with Smoke and Heat Control (SHC) by forced mechanical horizontal ventilation. They inves-tigated the influence of the SHC system on the smoke movement in fire conditions. Their results indicated that improving the smoke extraction rate does not assist to take away the smoke if it is smoke trapped inside a re-circulation region. The authors did not devise a solution to the LMA 1.7 m human height in relation to obstruction free jet problem inter-ference.

The authors (Senveli et al., 2015) studied the performance analysis and interpretation of daily emission ventilation and fire ventilation system design in indoor parking lots with jet fans using CFD program. The study consisted of 8-storey parking lot of a major site with jet fans. The analysis on one storey of the parking lot was provided as a case study. The most suitable jet fan placements were determined for daily emission and fire ventilation, and ac-curacy of this placement has been proved through the analysis. The study did not considerthe obstruction in CFD analysis.

2.4.2 Numerical CFD Description

The governing differential equations for continuity, momentum, energy, species, and turbulence transport were solved using the CFD package ANSYS FLUENT® 14.0 and can be expressed in Equation 2.6 (Versteeg, & Malalasekera, 2017).

$$\frac{d}{dx_i}(\rho U_i \Phi) = \frac{d}{dx_i}(\Gamma_\phi \frac{\delta \Phi}{\delta x_i}) + S_\Phi \tag{2.6}$$

where ρ is the air density, U_i is the velocity vector, Φ is a dependent variable (scalar or vector). The FLUENT software utilizes the finite volume method to solve these governing equations.

Table 2.2: Differential equations for continuity values of $\Phi, \Gamma_\Phi, S_\Phi$ (Khalil, & Gomaa, 2017)

Equation	Φ	Γ_Φ	S_Φ
Continuity	1	0	0
U-Momentum	U	μ	$-\frac{dP}{dx} + \rho g_x$
V-Momentum	V	μ	$-\frac{dP}{dy} + \rho g_y$
W-Momentum	W	μ	$-\frac{dP}{dz} + \rho g_z + \rho g \beta \Delta t$
Enthalpy	h	$\frac{\mu}{\sigma_h}$	S_h
Species	Y	$\frac{\mu}{\sigma_i}$	S_i
Turbulence Energy	K	$\frac{\mu}{\sigma_k}$	$G - \sigma\epsilon$
Turbulence Dissipation	ϵ	$\frac{\mu}{\sigma_\epsilon}$	$\frac{\epsilon}{K}(C_1 G - C_2 \sigma\epsilon)$

where $\mu = \mu_1 + \mu_t$, $\mu_t = \rho C_u \frac{K^2}{\epsilon}$, $\sigma_k = 1$ $\sigma_\epsilon = 1.3$, $\sigma_h = 1$,$C_1 = 1.44$, $C_2 = 1.92$, $C_u = 0.09$,

Where G in 2.2;

$$G = \mu_t(2\left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial V}{\partial y}\right)^2 + \left(\frac{\partial W}{\partial z}\right)^2) + \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right)^2 + \left(\frac{\partial U}{\partial z} + \frac{\partial W}{\partial x}\right)^2 + \left(\frac{\partial V}{\partial z} + \frac{\partial V}{\partial y}\right)^2 \tag{2.7}$$

In Equation 2.7, the scalar Φ is considered for the local mean age of air. The LMA is defined as the average time for air to reach point P once it enters the room. The newest air is at the fresh air inlets whereas the oldest is at the exhaust points and stagnant air areas. The diffusion coefficient for the LMA can be numerically calculated from the effective viscosity of the air as represented in Equations 2.8 and 2.9 (Khalil, & Gomaa, 2017):

$$\Gamma_{\Phi} = 2.88 \times 10^{-5} + \frac{\mu}{0.7}. \tag{2.8}$$

$$T - T_{\infty} = 16.9\left(\frac{Q^{\frac{2}{3}}}{H^{\frac{5}{3}}}\right) \text{for} \frac{r}{H} \leq 0.18$$

$$T - T_{\infty} = 5.38\left(\frac{\frac{Q^{\frac{2}{3}}}{H^{\frac{5}{3}}}}{\frac{r}{H}^{\frac{2}{3}}}\right) \text{for} \frac{r}{H} \leq 0.18 \tag{2.9}$$

where the temperature T, is in $^{\circ}$C; the total heat release rate Q, is in Kw; and the radial position and ceiling height (r/H) are in m.

The results showed that the temperature is limited to the zone, where the fire is detected, and it is within an accepted range. The CO_2 mass fraction was presented and showed how the jet fans contributed in reducing the smoke density and hence improve the visibility. It was found that dividing the car park into zones was highly recommended and should be taken in the design of the jet fan system (Khalil, & Gomaa, 2017).

BRE probabilistic heat release approach was used instead of the entire car park area. The paper analysed the validity of computerised CFD and analytical through differential equa-tions of continuity as shown in Table 2.2. The author did not validate the results with experiments for the case study. Only jet fans analyses were done and the relationship with exhaust fans were not considered. There was no analysis of effect fire on fans, compartment and fans run continuously. Also, there was no VSD and half speeds of fans mentioned hence no energy-saving measures.

2.5 Critical Literature Review

Most of the research globally has made the assumption that car parks are entirely flat whereas in a car park, presence of the services such as sprinklers result to a very low headroom.

Most of these designs become impractical as the fans have to be installed below the beams or sometimes in the beam pockets. This causes resistance and turbulence resulting in dead zones which leads to the non-achievement of the LMA desirable air quality velocity of 0.1 m/s. Dead zones thus cause the impulse ventilation systems to be inefficient where functionality needs arise. Non optimized placement of jet fans, leads to more installed jet fans leading to high initial cost. All the literature review didn't perform jet fans placement optimization. The literature assumed that the car park had no barriers that are known to affect the flow of polluted gases leading to dead zones and LMA desirable air quality velocity of 0.1 m/s. (Lu et al., 2011) investigated the smoke control capacity of impulse ventilation system (IVS) in an underground car park. They simulated ten scenarios in an 80 m long, 40 m wide and 3.2 m height domain with a fire source simulating a car fire with a peak heat release rate of 4 MW (probabilistic approach) by using simulations tool Fire Dynamic Simulator version. Their results showed that the smoke control capacity of the impulse ventilation system was sensitive to jet fan numbers and the increment in extract rate is conducive to relay jet flows. They emphasized that high jet fan velocity may cause severe smoke re-circulation, though there was no attempt to eliminate dead zones as well as jet fans optimal placement.

(Xu et al., 2018) performed experiment analysis and investigation on numerical simulations on sprinkler system and impulse ventilation in an underground car park. It was found that with the impulse ventilation, there would be less smoke upstream of the fire, which is favourable for fire-fighters to put out the fire. Besides, there would be fewer sprinklers activated with impulse ventilation system, which will help to stabilize the water pressure of the sprinkler system. The author, did not formulate a solution to address dead zones elimination on entire car park and LMA analysis.

(Viegas, 2010) applied ventilation system for covered car parks and used impulse ventilation systems in order to control the smoke. Analytical model for the flow field near the ceiling of car park of area of study was done and a comparison with CFD simulations was done. The research failed to develop a solution on LMA analysis as well as addressing dead zones for both NPV and EM modes on the entire car park as well as obstruction interference. (Burlacu et al., 2018) developed a CAD model of a complex car park using a fire dynamics simulator. The three car park simulations were done based on the probabilistic approach of the area most susceptible to the occurrence of fire. (Jug, Petelin, & Bukovec, 2011).developed a CAD model of a complex car park using a Fire dynamics simulator. The simulations were done based on the probabilistic approach of the most fire occurrence of a standard 4 Mw heat release.

The garage was assumed to be wide open, with no barriers or smoke curtains. (Umamaheswararao, 2020) developed a CAD model of a complex car park with an area of 3, 500 m^2. (Amnian, Maerefat & Heidarinejad, 2016) performed an experiment in an underground car park in order to analyse air quality carbon monoxide concentration only. A CFD simulation was done for CO concentration. (Kmecová, Krajčík & Straková, 2019) designed a fire ventilation system with impulse jet fans for an underground car park. There was a comparison of fluid flow design calculations with the use of Computational Fluid dynamics. (Deckers et al., 2013) developed a scaled CAD model of a complex car park with dimensions of 28.5 m by 30 m by 2.4 m in height. A scale model of 3 m by 3 m experiment was developed. The car park analysis was only for the CO concentration; the same jet fans used for dilution were used for ventilation with no consideration of the structural and architectural barriers. (Rafat, H. Waked, Al. Jangi, 2010) analyzed underground car park to investigate air quality (CO) concentration only. A CFD simulation was done in order to determine the minimum concentration levels. The consideration of the fire zone was also studied by the researchers. The underground car park used in this study was 5, 290 m^2 in area with a height of 3.7 m. A comparison between CFD results and analytical correlations for fire modeling was made. The analysis was then performed based on design standards. After the design implementation, errors in functionality of the systems may occur. These errors are expensive to rectify once implemented.

Consequently, the essential contributions of this research are:

1. Devise a solution of using CFD Simulations to eliminate dead zones in relation to structural obstructions thus achieving best efficiency in design results during project implementation applications.

2. Devise a solution of using CFD Simulations to eliminate stagnant area in relation to structural obstructions and achieving air quality flow levels at 1.7 m LMA plane thus, achieving best efficiency in design results during projects implementation applications.

3. Ensure the velocity of streamlines is within desirable range during dead zones removal. and at 1.7 m LMA plane.

4. Jet fans optimization placement.

2.6 Summary of Research Gaps

There have been improvements in car park ventilation from convectional systems to impulse systems. However,the following were the indentified researcher's gaps;

1. Eliminate dead zones in relation to structural obstructions in an underground car park.
2. Jet fans placement optimization.
3. LMA air quality velocity levels analysis at 1.7 m LMA plane in relation to structural obstructions.
4. Validation experiment for the dead zones elimination and LMA for a carpark with obstruction.

CHAPTER THREE

METHODOLOGY

3.1 Case Study

Car park basements in Konza Technopolis City have been used in this study. The geometric characteristics of the car parks under study is summarized in Table 3.1. The car parks consists of two underground car park where one is completely enclosed and the other partially open on one side to the atmosphere.

3.1.1 Geometric Characteristics

Table 3.1: Summary of Geometric Characteristics of the Car park Under Study.

Level	Floor to ceilling Height (m)	Surface (m2)	Volume (m3)
Basement -1	3.6	4,950	17,820
Basement -2	3.6	6,750	24,300

3.1.2 Jet Fans Placement - Conventional Rule

The general rule of thumb of jet fans placement recommends that jet fans with a thrust force of 25 N should cover 300 m^2. Similarly for a 50 N to cover 450 m2 the jet fans should be spaced not more than 15 m apart laterally and not more than 30 m apart longitudinally for air-throw distance. The soffit was considered to be flat, and only jet fans with thrust options of 50 N and 25 N considered. For basement 2 the minimum and maximum number of jet fans were 15 and 23 in number given an area of 6, 750 m2. For Basement 1 the minimum and maximum number of jet fans would be 11 and 17 in number respectively for an area of 4, 950 m^2.

3.2 Model Development

The geometric representation of a car park model involves the specification and creation of complex curves, surfaces, and solid bodies in a virtual CAD environment, using different geometry defining technologies, with the most important being the approximation and interpolation. The car park walling and flooring is the part of the car park that, by architectural design, takes over the tasks involved in the construction of the car park, as well as the structure that holds the weight of the car park which is represented by beams and columns.

The car park mechanical system is the part containing its extraction system on the structure and it is affected by the architectural and structural geometry.

The general cross sectional arrangement of jet fans, and extraction fans in the car park is as shown in Figure 3.1. The car park under study as shown in Appendix I consisted of two car park levels; basement 1 and basement 2.

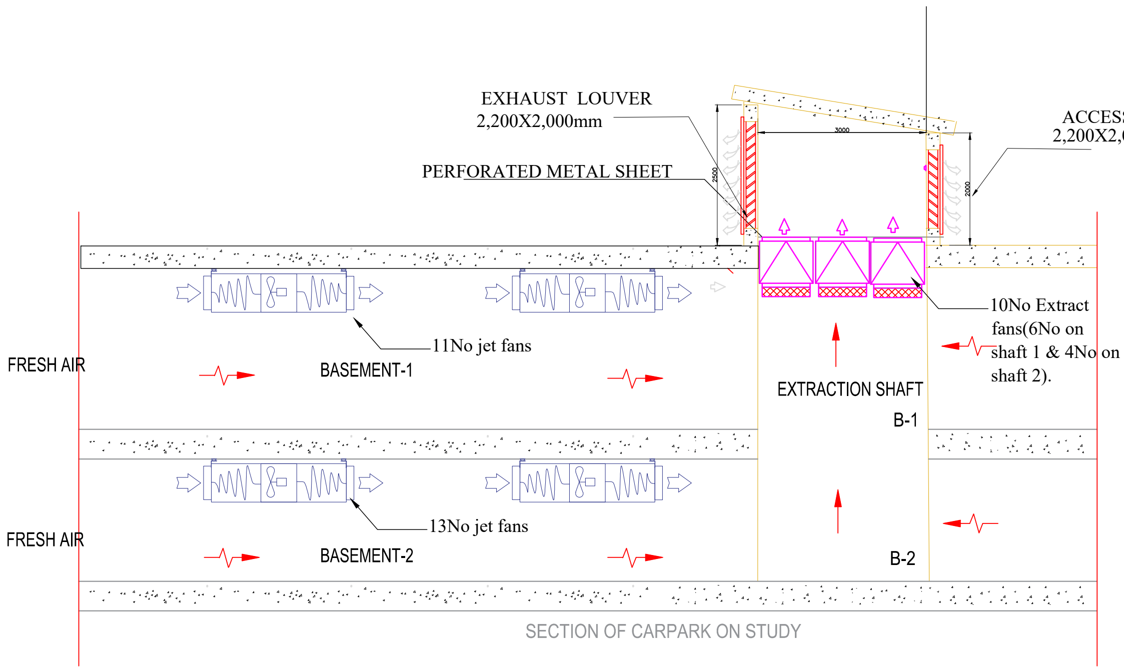


Figure 3.1: Typical basement schematic diagram of the car park on study.

Each car park was 86 m long, 79 m wide, and 3.6 m high having down stand beams of 750 mm. The plinth area was 4, 950 m^2 and 6, 750 m^2 for basement 1 and 2, respectively as summarized in Table 3.1. The car park consisted of two ramps with one on the lower left on basement 1 and another at the middle of which interconnects Basement 1 and 2. Ramp 1 connects the car park directly with street-level; hence, it was treated as open to the atmosphere. The interconnecting ramp in the middle is considered sealed on the sides so that air could only pass through the respective exit. Natural fresh air opening shafts (FA-11 and FA-12) are provided with each of total free area of 6 m^2 on the extreme left as well as two extraction shafts each having a total free area of 7.02 m^2. Zoning for operation is done for each level in conformity with design standards operations and functionality. The dimension of the extraction points as summarized in Table 3.2 where the dimensions are for the, exhaust grills actual area and their respective free area.

Table 3.3 shows the airflow and velocity of air at the exhaust points EA-11 and EA -12 for both basement 1 and 2 during the NPV and during the EM. All the points are mechanical extraction points with fans (Kioi, Njiri, & Wanjiru, 2022).

Table 3.2: Dimensions of Extraction Points of the Car Park Under Study.

Level	Designation	Width (m)	Height (m)	Actual area (m2)	Free area (m2)
Basement -1	EA-11	2.65	2.65	7.02	5.6
	EA-12	2.65	2.65	7.02	5.6
Basement -2	EA-11	2.65	2.65	7.02	5.6
	EA-12	2.65	2.65	7.02	5.6

Table 3.3: Airflows at Extraction Points for NPV and EM modes.

Level	Designation	Flow rate NPV (m3/hr)	Velocity NPV (m/s)	Flow rate EM (m3/hr)	Velocity EM (m/s)
Basement -1	EA-11	43,738	2.76	77,896	5.53
	EA-12	86,798	2.76	144,664	5.53
Basement -2	EA-11	53,651	2.95	89,418	5.89
	EA-12	99,637	2.98	166,062	5.98

The exhaust and supply points of the main fans are on the extreme ends of the floor layout respectively. Scientific calculations for the multiple inlet and outlet points is based on Vickery models standard orifice flow equation through the ith aperture (Yoon, & Malkawi, 2017). In the procedure, aperture means the sum of all open areas on a wall for low rise buildings or an individual opening for high rise buildings.

The flow Q through the i^{th} aperture is given by:

$$Q_i = Cd_i A_i V_{ref} \frac{[Cp_i - CP_I]}{[|Cp_i - CP_I|]^{\frac{1}{2}}} \qquad (3.1)$$

Cd_i is the ambient discharge coefficient for the i^{th} aperture with 0.62 as the recommended value. A_i is the area of the i^{th} aperture, V_{ref} is the reference velocity, Cp_i is the pressure coefficient for the i^{th} aperture and Cp_I is the internal pressure coefficient. Iteration solution is then obtained with the first two starting values of CP_I.

Both ventilation was exhausted out with the help of a mechanical ventilation system. The capacity of air flows for extraction points; EA-12 and EA-12 has been calculated and tabulated as in Table 3.3.

3.2.1 Geometry Creation

Architectural CAD floor layouts shown in Appendix I were used for the placement of the jet fans and CO sensors. The CAD model for the two basement floor layouts was transferred to the Revit CAD where the Revit architect feature was used to add the walling and structural features (Kurowski, 2019). All the mechanical, structural, and architectural features were added, making the surface CAD model exactly as per site conditions. The air extraction points and fresh air points were also added as shown on the 3D model in Appendix II. The created Revit model was then transferred to Solid Works, for CFD analysis meant to identify the dead zones. BIMDex Revit to Solid Works Exporter was used as an intermediate tool in order not to lose geometric correlation properties of the revit model (Kioi, Njiri & Wanjiru, 2022).

3.2.2 Governing and Solver Equations

The governing differential equations for continuity, momentum, energy, species, and turbu-lence are used in simulations. Flow solves using the Navier-Stokes equations which include mass, momentum and energy conservation laws were expressed in the equations 3.2, 3.3, and 3.4 as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{3.2}$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial[\rho u_i u_j]}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho f_i \tag{3.3}$$

$$\frac{\partial(\rho e)}{\partial t} + (\rho e + p)\frac{\partial u_i}{\partial x_i} = \frac{\partial(\tau_{ij} u_j)}{\partial x_i} + \rho f_i u_i + \frac{\partial(\dot{q}_i)}{\partial x_i} + r \tag{3.4}$$

In the conservation equations 3.2, 3.3, and 3.4, ∂ represents algebraic operator thermodynamic variable in order to get a solution. ρ is the density, where p is static pressure, τ_{ij} is viscous stress tensor and ρe is the gravitational force per unit volume. These equations are supplemented by definitions of empirical nature of fluid density, viscosity and thermal conductivity on temperature of fluid state equations. Solidworks considers both laminar and turbulent flows (Sobachkin, & Dumnov, 2013). Transport equations for the turbulent kinetic energy and its dissipation rate are used in the simulations using k – ε model. The k – ε turbulence model with damping functions describes laminar, turbulent, and transitional flows of homogeneous fluids consist-ing of turbulence were calculated using the equations 3.5 and 3.6. The term G_k is the result of turbulence energy due to mean velocity gradients, G_b is the product of turbulence energy due to buoyancy effect and μ_t is the viscosity of turbulence. For realizable k – ε model, the turbulence kinetic energy k and its dissipation rate ε, is represented as;

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_K + G_b - \rho\varepsilon - Y_M + S_k \qquad (3.5)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{K}(G_K + G_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}(G_K + S_\varepsilon \qquad (3.6)$$

where for all the constants in the above equations; $\mu = \mu_1 + \mu_t$, $\mu_t = \rho C_u \frac{K^2}{\epsilon}$, $\sigma_k = 1$ $\sigma_\epsilon = 1.3$, $\sigma_h = 1$, $C_1 = 1.44$, $C_2 = 1.92$, $C_u = 0.09$ [30].

3.3 CFD Model Setup: Processing

3.3.1 Processing

This phase of a problem included all the steps from the initial problem from the beginning of computations to simulations. This included the geometry creation, mesh generation, model selection, fluid property specification, and enabling and setting up the models (such as k- for turbulence). The created 3D CAD model was then transferred and run in the CFD program in this case (Solid Works 2019), with the rest of the work thereafter being performed and completed by same program. After opening the model in the CFD program, the model was checked for containment on the computational domain; assigned to each fluid and volume.

After this, the boundary conditions were determined and all the necessary calculation values were performed. These calculations include: air intake, exhaust flow rate values at the point where free air jet fans are blowing air into the parking lot, temperature inputs and outputs; pressure locations were set to zero or atmospheric. The next step was to determine the goals expected in the flow simulation iterations which was affirmed. The determination included the velocity, volume flow rate and heat if required which can be either low, average, or high ranges. The final step before the simulation iterations in the process was meshing. Where the mesh number is too large, the iteration by the program may proceed albeit with difficulty, making the process time-consuming. The opposite extreme also presents a problem with accuracy since a low mesh number may not give accurate results. This then leads to the solution stage where the calculation iterations are run. These CFD-simulated complex system models for underground car parks will be useful in research subjects and especially in the design of ventilation systems.

3.3.2 Boundary Conditions

At this phase, the scope of the geometry that was being studied was determined. This included the air velocity, flow condition known at the inlets and the outlets and the associated environmental pressure.

1. The air inlets have a volume flow rate and specified values of velocity for both NPV and EM.
2. The flow volume for the three fresh air inlets in basement 1 were all assigned as 12.36 m^3/s, For basement 2;- inlet 1 was 46.67 m^3/s, inlet 2 was 31.11m^3/s and inlet volume flow 3 was 10.13 m^3/s.
3. The environmental pressure was taken as 101,325 Pa
4. The walls and beam functions were used to calculate the wall shear stress as per AutoCAD Revit library.

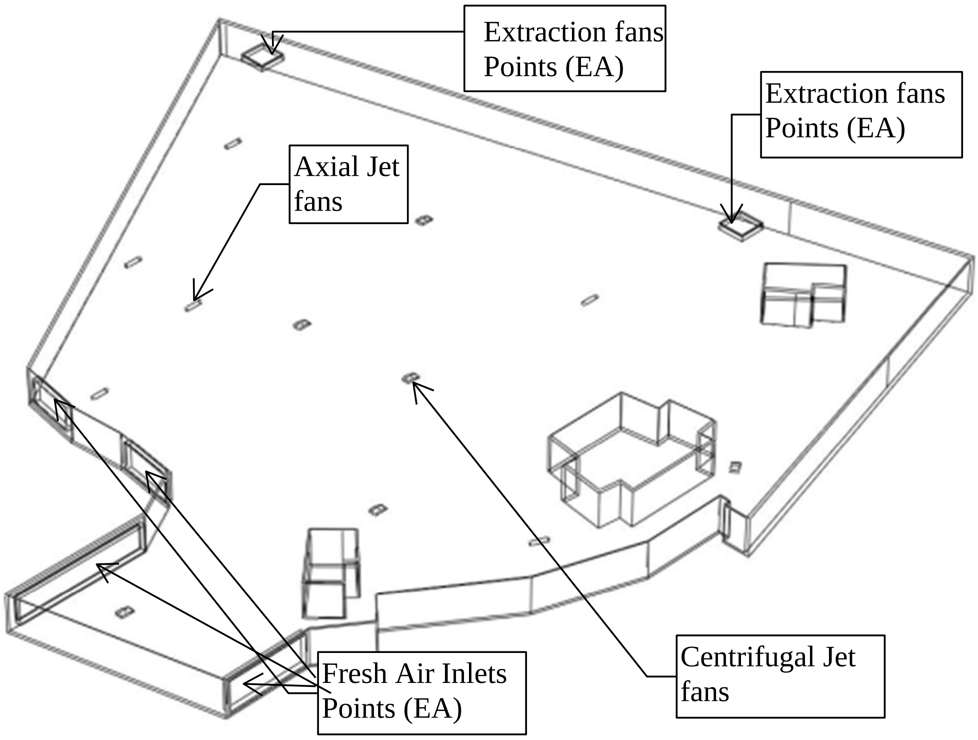


Figure 3.2: Computational domain and fluid sub-domain for basement 1

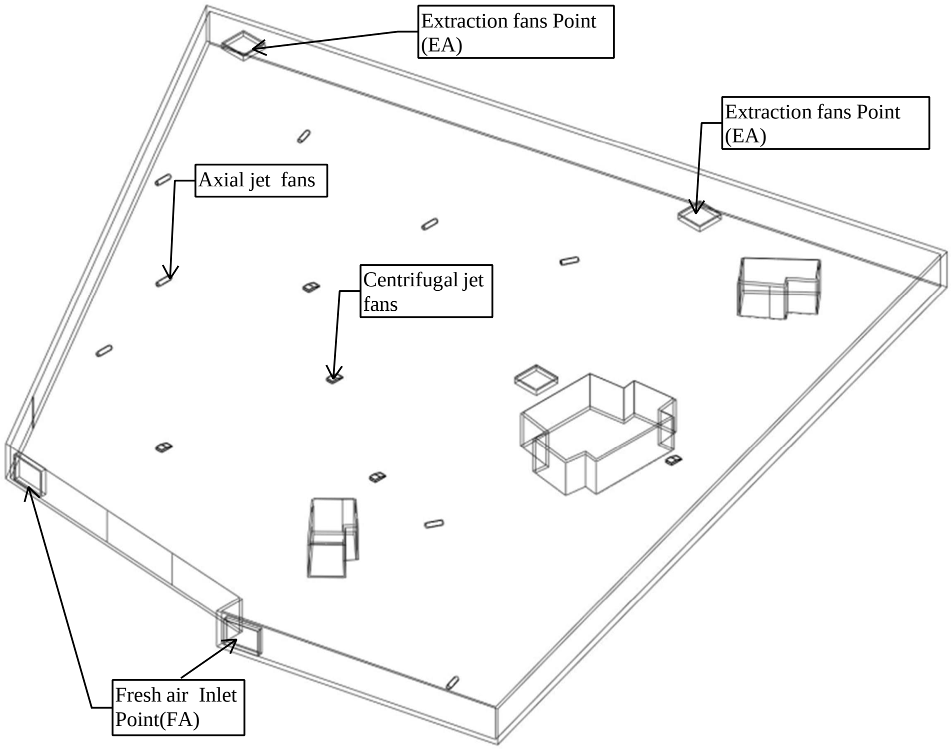


Figure 3.3: Computational domain and fluid sub-domain for basement 2

Figure 3.2 and Figure 3.3 shows the computational domain and fluid sub-domains for case study both for basement 1 and 2 respectively. The geometry shows boundary conditions on how the air enters through the fresh air (FA) points and how it exits towards the Exhaust points (EA). One of the air inlets points has been taken as Environmental pressure point (10,1305 Pa). Both the geometry on Figure 3.2 and Figure 3.3 show the induction jet fans which push air toward the extraction points.

3.3.3 Meshing

Meshing was the final critical step in CFD analysis of the car park. The solidworks global mesh settings were set to generate the required, (based on a global element size), tolerance, and local mesh control specifications. The mesh control automatically assigned different sizes of elements for components, faces, edges, and vertices's of the car park model. The software estimates a global element size for the model taking into consideration its volume, surface area, and other geometric details. The goal was to create an accurate mesh without excessive cells to allow an efficient and accurate solution to be generated. The meshing generated 3D tetrahedral solid elements, 2D triangular shell elements, and 1D beam elements. The mesh specified consisted of mixed type solid elements. Shell elements generated were for modeled thin parts of walling and beams for the structural members of the car park as per geometric characteristic. The contour image results of cut plots after simulation at the required planes were generated for analysis.

Table 3.4: Input/output Operation of Fans for Energy Saving.

Mode	**Normal Pollution Ventilation (NPV)**		
	Sensing	Extract Fans	Jetfans
A	CO < 30 ppm	Off	Off*
B	CO = 30 ppm	Low Speed	Low Speed
C	CO ≥ 90 ppm	High Speed	High Speed
Mode	Emergency smoke clearance Mode (EM)		
D	Smoke or rapid Temperature rise	High Speed	High Speed**

From Table 3.4, (*) denotes that dilution during operation of CO pollution will be possible with some jet fans running at low speed. For smoke clearance systems (**), denotes that the main extract fans were to be operated immediately, whilst jet fans or Induction fans were to be operated at a predetermined delay before operation.

Table 3.5: Summary of Jet Fans Placement Recommendations According to Manufacturer.

Newton thrust	**Longitudinal spacing (m)**	**lateral spacing (m)**	**Area of coverage (m^2)**
25N-Axial jet fans	40	6	200
50N-Centrifugal jet fans 1	68	8	400

According to Table 3.5, the different type of jet fans (25 N and 50 N) serves a specific area of 200 m^2 and 600 m^2 both laterally and longitudinally respectively. The data for lateral and longitudinal spacing of jet fans as shown in Table 3.5, was taken from the jet fan's manufacturer catalogue used in the case study from Sola Palau (S & P®) fans shown in Appendix III.

3.4 Optimization of the Placement of Jet Fans

In order to eliminate dead zones, it is important to have jet fans optimally placed in a car park while considering the car park design (Puchongkawarin et al., 2013).

Table 3.6: Jet Fans Optimization Programming Problem.

Jet fans required (No)			
Spacing	25 N-A (No)	50N-C (No)	Maximum No that can be installed (No)
Longitudinal	40	68	12
Lateral	6	8	12
Cost per unit	\$ 1,500	\$ 2,000	

Table 3.6 shows the two types of fans (25-N and 50N-C) and their respective lateral and longitudinal spacing as well as the unit cost in USD (\$). Installations were for the area of 6, 750 m^2 and 4, 950 m^2 corresponding to basement 2 and 1 respectively. The problem was to determine the least number of jet fans for basement 2 and 1 in order to reduce the cost for comparison to traditional conventional rule of thumb.

The general optimization problem is given in Equation 3.7 (Venkataraman, 2009).

$$\min f^T X \tag{3.7}$$

subject to the constraints in Equation 3.8;

$$\begin{cases} AX & \leq b \\ A_{eq}X & = beq \\ L_b \leq X \leq U_b & \\ X & = \{x, y\} \\ X \in N & \end{cases} \tag{3.8}$$

where, the $f^T X$ represents the objective function to be minimized, X consists of the decision variables that is a vector representing the optimal number of jet fans. A, denotes matrix associated with inequality constraints, and b is the vector related to the inequality constraint; A_{eq} represents the matrix associated with equality constraints and b_{eq} is vector associated with linear equality constraints; L_b is the lower bound vector, and U_b is the upper bound vector of the decision variables.

Consideration was made on the constraints due to the minimum limitations on the jet fans, and that from Table 3.6, the jet fans to be serving a specific area both laterally and longitudinally. Considering operation discretion approach on longitudinal throw of flow of jet fans to avoid turbulence that might arise from walling of staircases and ramp non wastage of energy, the area to be served by 25 N fan would be 2, 250 m^2 while the area to be served by 50 N centrifugal fans would be 4, 500 m^2. Since the total area for basement 2 was 6, 750 m^2, while a combination area of coverage of the two different fans is 600 m^2, a maximum of 12 fans are required. By Letting the two different jet fans (25N-A and 50N-C) be installed and be denoted by x and y, respectively. This resulted in the formulation of Equation 3.10. The same procedure was repeated for basement 1.

$$\frac{2,250}{6,750}x + \frac{4,500}{6,750}y \leq 12 \tag{3.9}$$

which simplifies to;

$$\frac{1}{3}x + \frac{2}{3}y \leq 12 \tag{3.10}$$

Considering the two types of jet fans and according to Table 3.6; the 25 N and 50 N based on the area, the relation of number of jet fans would be;

$$\left(\frac{40 \times 6}{600}\right) x + \left(\frac{68 \times 8}{600}\right) y = \left(\frac{9,750}{600}\right) = 12 \tag{3.11}$$

which simplifies to;

$$0.4x + 0.9y = 12 \tag{3.12}$$

Therefore in Equation 3.8, the case study constraints are; $A = [\frac{1}{3}, \frac{2}{3}]$ $b = 12$, $A_{eq} = [0.4, 0.9]$, $b_{eq} = 12$. From subsection 3.1.2, $L_b = [0, 0]$ and $U_b = [15, 23]$.

The total cost in United States Dollar ($) of fans relation, is the objective function considered to be maximized in the case study would be related as;

$$\$f(x, y) = 1500x + 2000y \quad (3.13)$$

Thus the problem was to determine the non-negative values of x and y that satisfy the constraints stated is given by Equation 3.10 and Equation 3.12 and maximize the objective function given by Equation 3.13. This provided an integer linear programming problem given that the control variable representing the number of fans to be used can only take positive integer values.

3.5 Computational Domain Analysis to Remove Dead Zones and for LMA at 1.7 m Height

The simulations CFD procedure followed was as shown in Figure 3.4. The Revit 19 model of basement 1 and basement 2 as shown in 3D CAD model in Appendix II was transferred to Solid Works simulation software. So as not to lose the geometry parameters from Revit to Solid Works, Draftsight tool was used as an intermediate tool. This was also done to include total impulse fans layout and extraction and supply points. After exporting the model to the CFD program, every material was assigned to each fluid and volume, until there was no volume left unassigned (Sobachkin & Dumnov 2013).

From Sola Palau (S & P®) fans manufacturer catalogue (Palau, 2021) jet fans were modeled at a flow rate of 1.35 m^3/s through a nozzle 600 mm wide by 100 mm high. The centreline velocity at the outlet is approximately a maximum of 15 m/s and the nozzle directed air flow downward where appropriate. Optimized appropriate location for jet fans in the down stand beams of size 750 mm and pockets of size (8 by 7.5 m) was used on simulation as determined in CAD layout. In the case study, headroom of the car park was at 2.85 m, thus no installation of jet fans could be allowed below it. The initial approximate capacity and number of jet fans was achieved using the rule of thumb on floor layout shown in Figure 3.1 and Figure A.1. This was done according to Figure 2.3 which considers jet fans not to be placed more than 15 m apart on sideways and not more than 30 m apart in terms of through distance.

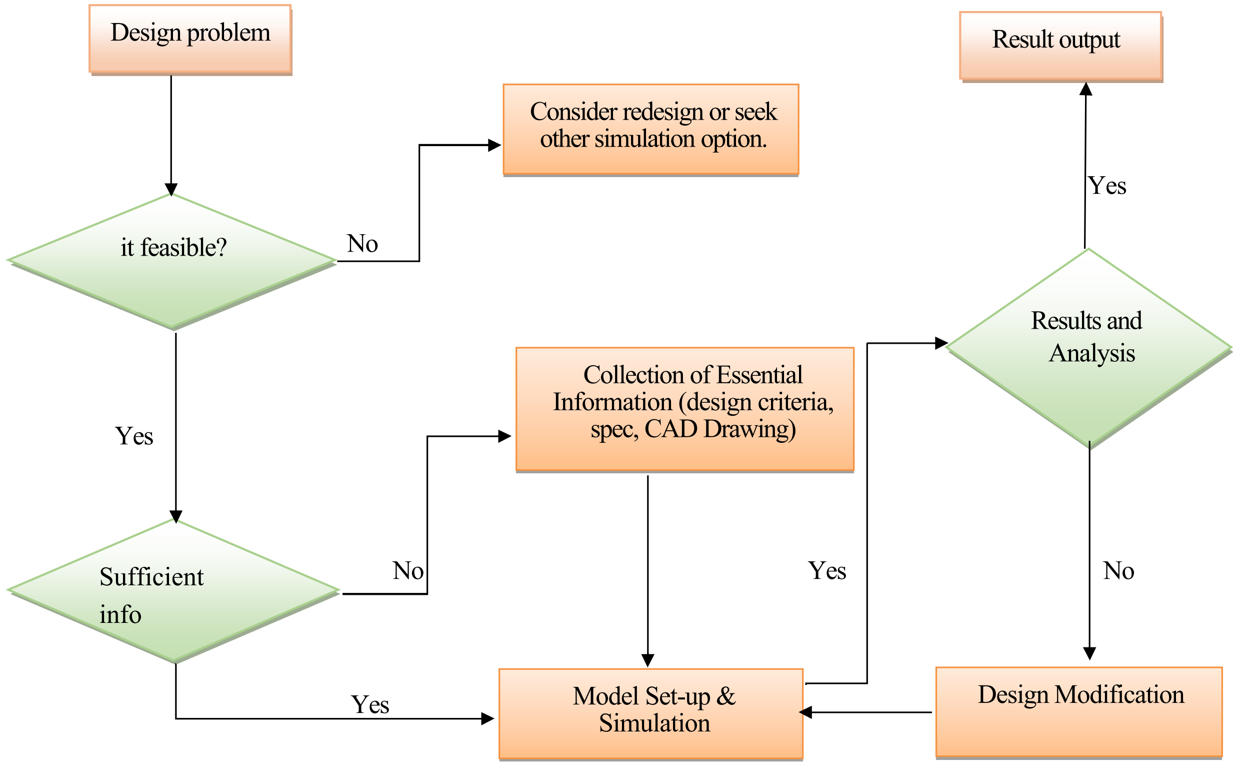


Figure 3.4: CFD Simulations procedure summary.

Determination of whether fans required at fresh air supply was determined at this point considering the rule of thumb of natural opening being greater than 2.5% of floor area. The summary of the jet fans and exhaust fans was determined and tabulated. After this fan placement process, the boundary conditions were determined, i.e. all the necessary calculation values were entered such as air intake and exhaust flow rate values at the point where jet fans blow air into the parking lot, zero pressure locations, temperature inputs and outputs, and so on. During operation, the law of conservation of mass is satisfied, which states that if the total mass flow rate is not equal to the total mass flow rate of the outlets then at least one pressure opening condition needs to be provided through the law of conservation of mass.

Local Mean Age of Air CFD was analysed which the airflow regarding the velocity of air to show the air distribution in the car park. This is the parameter of air quality at 1.7 m height above the floor (adult height and jet fans plane) as shown in Figure 3.5. Though there are no international standard restrictions on LMA. As stated earlier, the LMA is the average time for the air to reach the arbitrary point of the underground car park since air entry into the underground car park. The concept of LMA helps in re-positioning and determination of the optimal number of jet fans. Increasing the number of jet fans does not improve mechanical

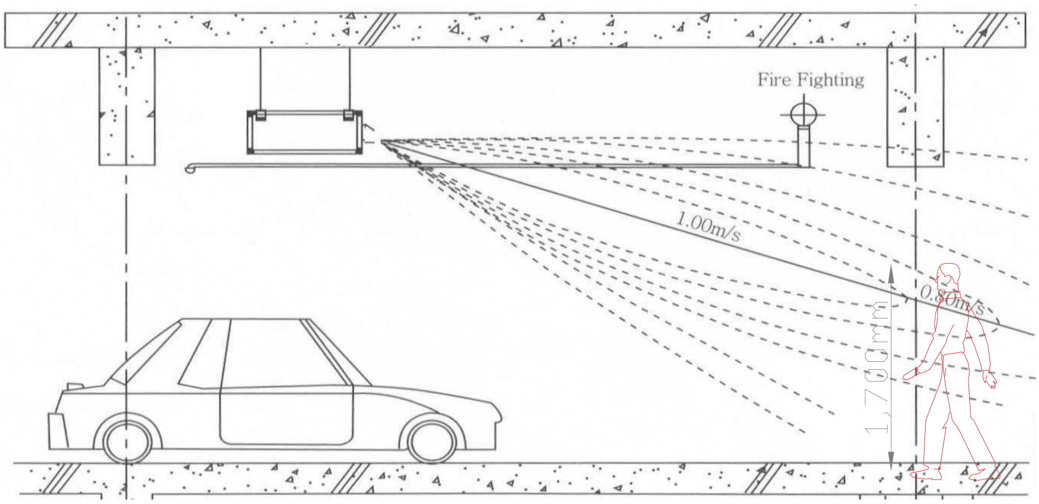


Figure 3.5: Sketch on LMA 1.7 m height.

The computational domain used for this analysis was done using Solidworks on the entire space. The boundary conditions were determined by means of all the necessary calculation values determined such as air intake and exhaust flow rate values at the point where jet fans blow air into the parking lot, zero pressure locations, temperature inputs and outputs, and so on. In order to save energy on operation of fans, the airflow's rates was done for both low and high speed of the devices.

From S & P fans manufacturer and jet fans modeling capacities parameters as stated earlier, analysis was done for the air velocity to ensure no stagnation of air. Air velocity of 0.1 m/s, or greater was to be considered desirable. Determination of LMA is at the air re-circulation at 1.7 m Height. The LMA value of these parameters would be 720 seconds according to 5 ACH for the NPV scenario and 360 seconds according to circulation of 10 ACH for the EM (Senveli et al., 2015). Appropriate location for jet fans was compared with CFD dead zone analysis in the car park. Simulation was done until acceptable and recommendable velocity at plane 1.7 m for the basement in m/s for the NPV Mode. The velocity streamline of particles say 60 going through the jet fans in 360 sec after being released from jet fan was simulated. The simulation results was then generated and documented.

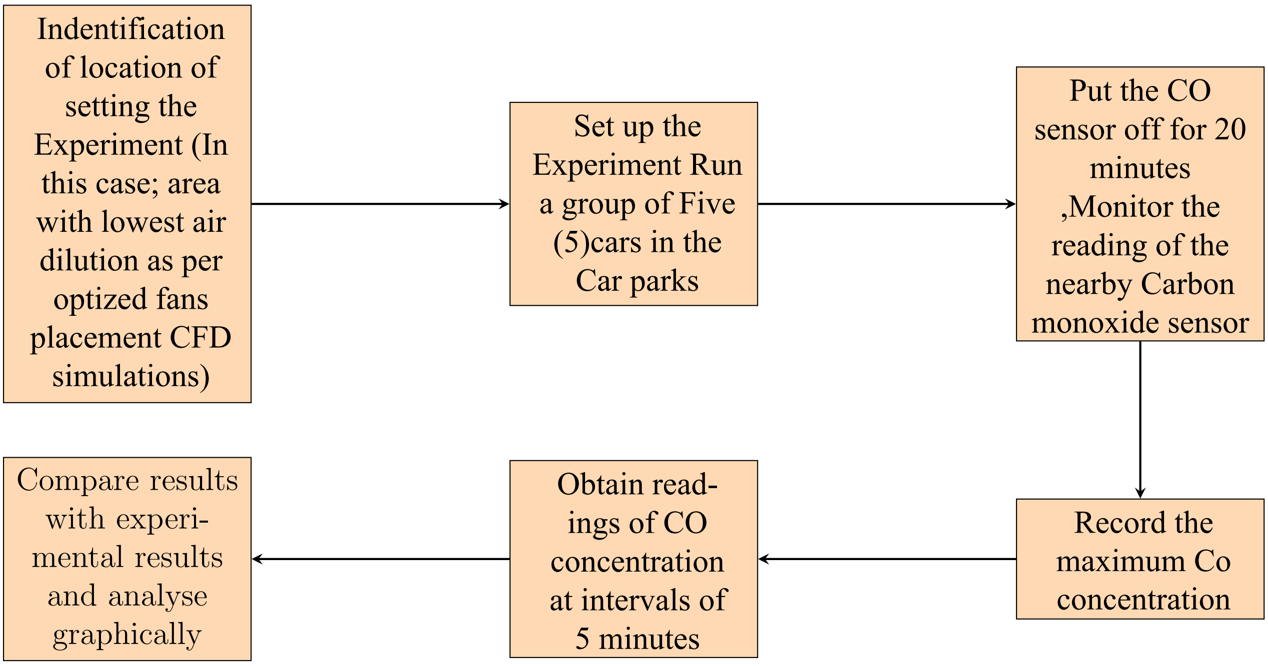


Figure 3.6: Summary of the experimental procedure for dead zones elimination and air quality validation.

3.6 Experimental Validation

3.6.1 Dead Zones Coverage and Air Quality

An experiment was set up as shown in Figure 3.6. The simulated optimized jet fans location CFD layouts were used as a guide on the most probable area of experiment. This was identified as the areas with the most stagnant area i.e zero velocity. B11 to B22 represented the experimental measurement points where readings were taken. These points were B11, B12 and B21, B22 for basement 1 and 2 respectively. The experimental sample velocities measurement points taken were B11, B12, B21 and B22 as shown on Figure 4.7 and Figure 4.10. The location of points was guided by the fact that these are the driveway routes areas as shown in Appendix I, where all car passes to and fro from parking bays hence the possibility of high CO concentration and as well areas with almost dead zones according to simulations results. A group of five (5) cars were driven in the two basements at 46.25 mg/s. This was taken from the consideration that the CO emitted by each car is taken as the average of hot and cold engine emissions maximum allowable extremes average (National Fire Protection Association, 2021). The total carbon monoxide concentration is given by the number of cars in the car park in consideration of the percentage of active cars their CO emitted by each car. In this regard, five cars were sufficient to cause above the safe limit of CO level in the car park to trigger the CO sensors.

They passed through the driveways on the most probable areas where dead zones were expected to occur during the jet fans optimization. The jet fans control system were first put off, then actuated after 20 minutes as shown in Figure 3.6. By this, the accumulated CO concentration would have gone up and consequently an effect was observed on the CO sensors. The behaviour of nearby jet fans was observed in response to the CO concentration and recorded at intervals of 5 minutes. The response of the nearby CO sensor showed if, the dead zone has been eliminated.These were stagnant areas (almost to no air velocity) in reference to Figure 4.1 (b) and Figure 4.2 (b). The velocities measurement points (B11 to B22) and CO concentration are as shown in Figure 4.7 and Figure 4.10. The jet fans were shut off for about 20 minutes in order have substantial projection readings on the jet fans. The essence was to ensure the jet fans do not dilute the dead zones at low concentration. The level of CO concentration was observed on sensors installed in close proximity to expected dead zones. The concentration of carbon monoxide was observed for over an hour and averaged at intervals of 5 minutes. The behaviour of nearby jet fans were observed in response to the CO concentration. The results were observed and recorded.

3.6.2 Flow Rates of Entire Car Park Model

Experiment procedure was set up as shown on Figure 3.7 where all the main extraction fans and jet fans were run. Fresh air inlets from (FA-11) to (FA-22) points as well as two other separate airflow points were measured for each of the basement at the Driveway points (DR-1 DR-2, and DR-3) for basement 2 for Emergency ventilation scenario with measurement points as shown in Figure 4.10. The results obtained were tabulated and compared to simulation results for both the NPV and EM modes in line with flow rates. The proximity of the results ascertained the accuracy, in reference to the dead zones removed.

3.6.3 Air Flow of Entire Car Park Model at 1.7 m LMA Plane

One experiment was set up as shown on Figure 3.8 where all the fans; main extraction fans and jet fans were run. Fresh air inlets from (FA-11) to (FA-22) points as well as two other separate air flow were measured for each of the basement at the driveway points (DR-1,

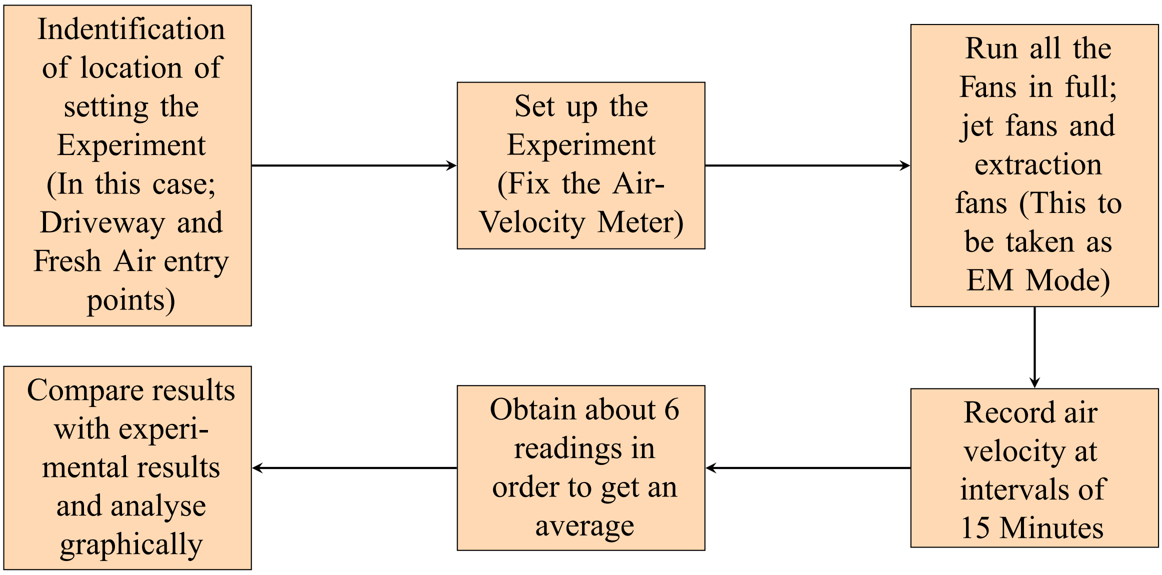


Figure 3.7: Experimental procedure summary for air flow model validation. DR-2 and DR-3) for the two basements for both ventilation scenarios.

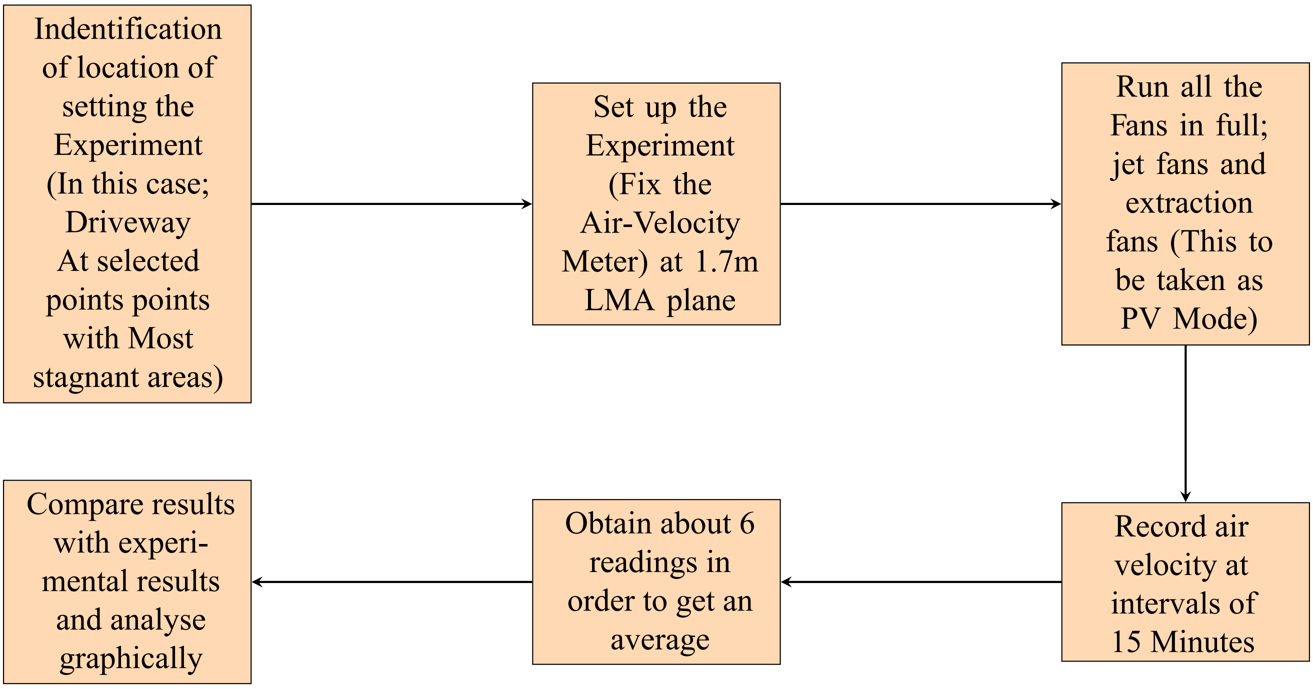


Figure 3.8: Experimental procedure summary for air flow rate model validation for 1.7 m LMA.

The results obtained was tabulated in comparison with simulation results for the NPV only mode in line with flow rates. The CO concentration was also measured at the same LMA plane and the results recorded for analysis. The proximity of the results ascertained how the simulation model accuracy was in reference to the dead zones removal. The LMA value was 720 seconds according to 5 ACH air circulation for NPV Scenario and 360 seconds according to 10 ACH air circulation for EM.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Car Park CFD Model with Conventionally Placed Jet Fans

Simulation results were obtained for the two car parks under consideration on Basement 1 and Basement 2. This was for the two scenarios; Normal Pollution Ventilation (NPV) and Emergency Mode (EM). The key was the analysis of air flow with regard to velocity as they show the air distribution in a car park.

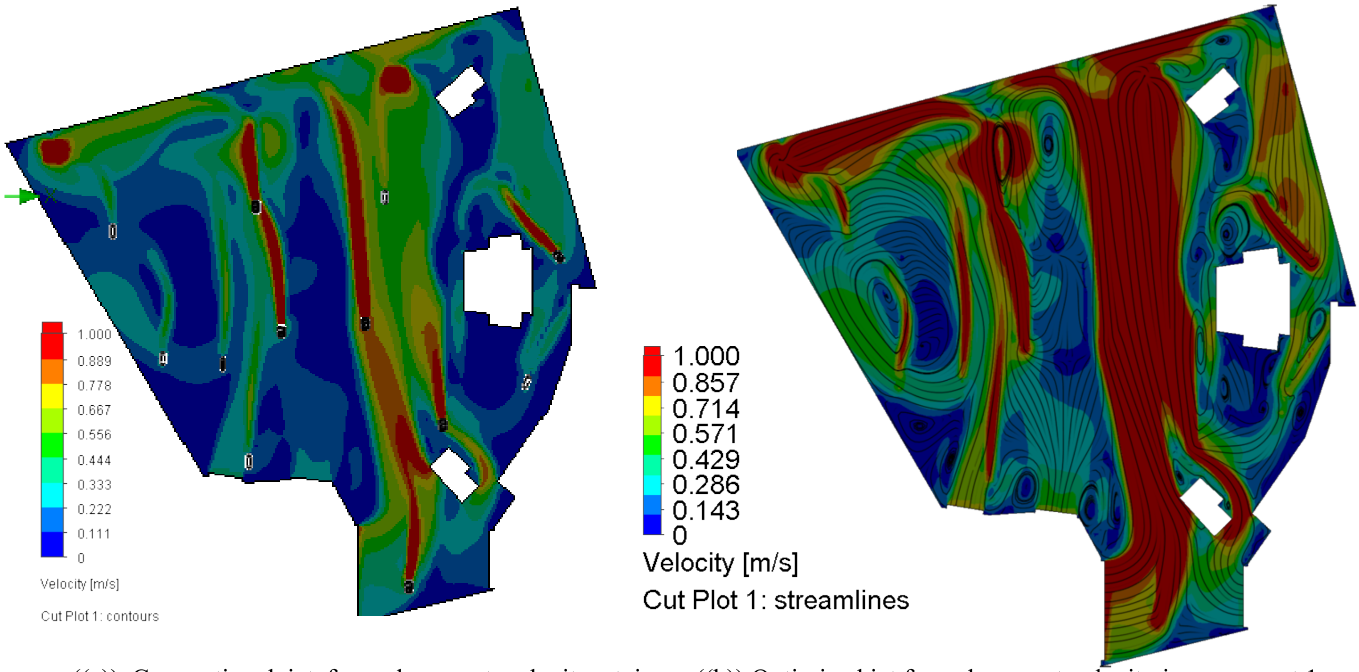
The essence of the analysis was to ensure that there was no significant stagnation of air (dead zones). Air velocity of 0.1 m/s or greater is normally considered desirable (Palau, 2021). The parameters were plotted for the jet fan plane contours and their associated streamlines.

4.1.1 Normal Pollution Mode

The steady simulations images showed the different aspects of air flow and performance for both NPV and EM with the following constrains; Iterations of 308, Fluid Cells of 3,783,822, and Particle Cells of 650,065.

The contours and steamlines in Figure 4.1 (b) shows how air enters the car parks and how it exits. The simulations results also show the streamlines going through the jet fans in each of the two basements. In addition, the simulation clearly shows how the fresh air inlet values as tabulated in Table 4.1. As depicted in Figure 4.1, effects on jet flows velocity obstructions were obtained both for Basement 1 and 2 respectively. The scale ranges in Figure 4.1 and Figure 4.2 ranged from 0 to 1 m/s and to 2 m/s in velocity for both NPV and EM respectively. Zero velocity (0) had dark blue colouration meaning stagnation of air; hence, dead zones. Since 0.1 m/s is considered desirable, therefore in Figure 4.1 (b) and Figure 4.2 (b) it is evident there was a lot of reduction in dead zones.

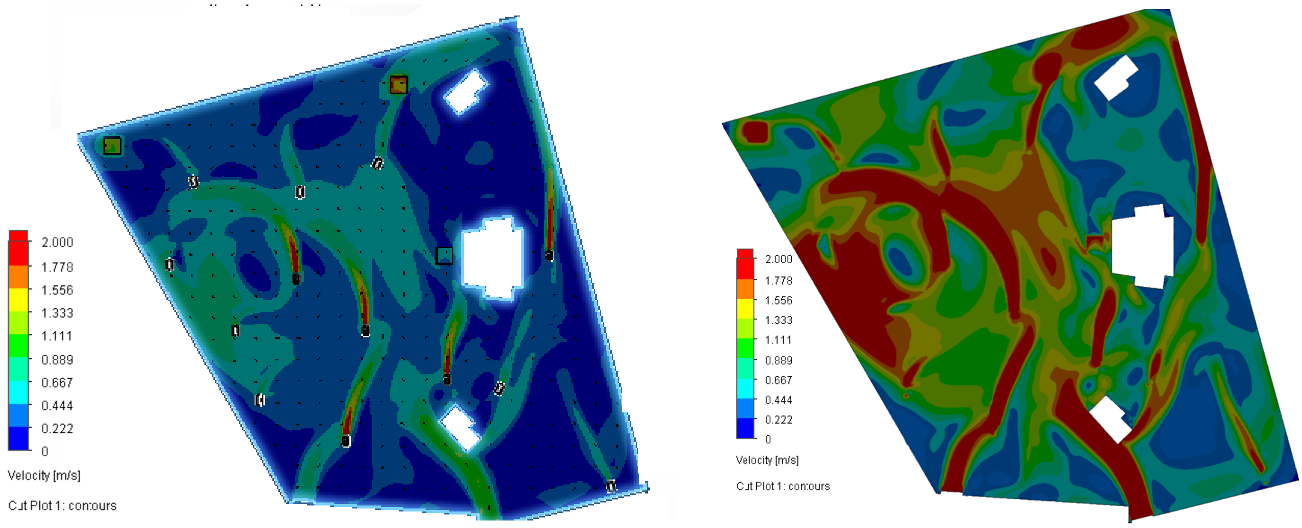
The stagnation and re-circulation was drastically reduced by changing the jet fans capacity and adjusting the flow angle in line within the 8 m by 7.5 m down stand beam pocket as shown in Figure 4.1 (b) and Figure 4.2 (b) both for basement 1 and 2, respectively. The velocity streamlines as shown in Figure 4.3(a) and Figure 4.3 (b) shows the velocity streamlines during operation in elimination of stagnant areas as shown in Figure 4.1 (a) and Figure 4.2 (a). This shows about 99% stagnant areas reduction which would have a lot of significance on operation of these systems.



((a)) Conventional jet fans placement velocity at im-pulse fans plane basement 1 of the car park analysis.

((b)) Optimized jet fans placement velocity in vase-ment 1 at impulse fans plane for NPV Scenario.

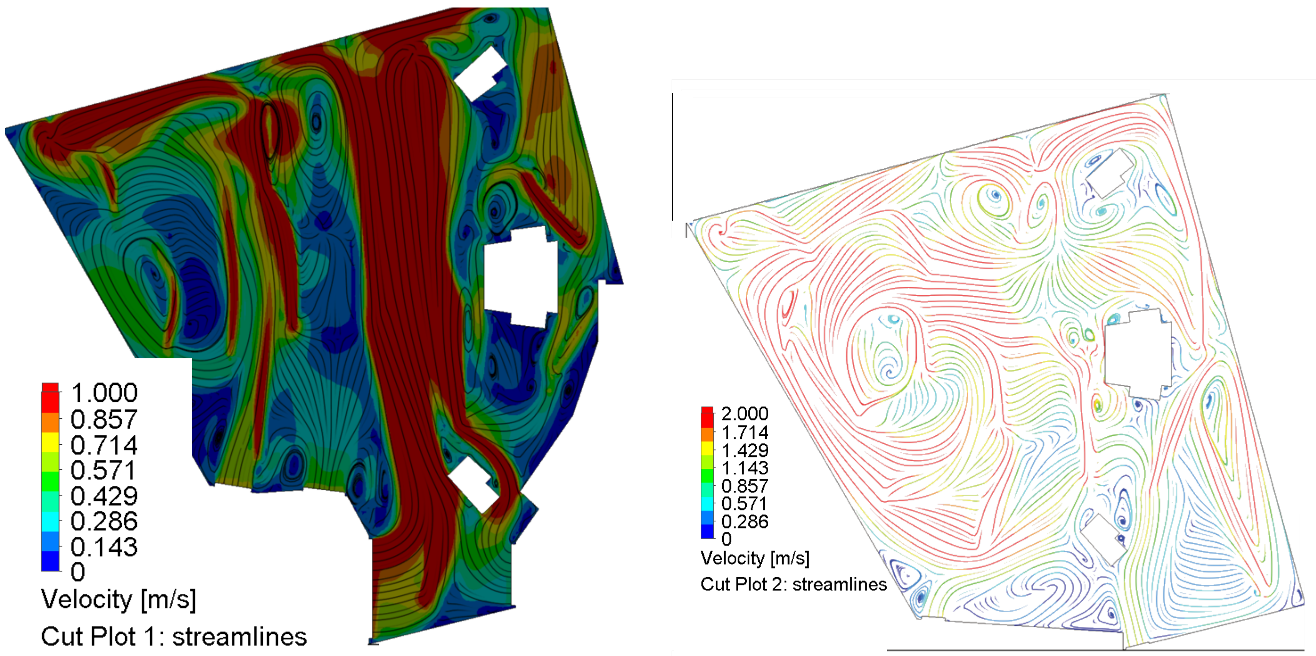
Figure 4.1: Comparison between convention and optimized jet fans placement velocity anal-ysis at impulse fans plane for NPV scenario for basement 1



((a)) Conventional jet fans placement velocity at impulse fans plane basement 2 of the car park analysis.

((b)) Optimized jet fans placement velocity in basement 2 at impulse fans plane for NPV Scenario

Figure 4.2: Comparison between convection jet fans with optimized jet fans placement velocity analysis at impulse fans plane for NPV scenario for basement 2



((a)) Optimized jet fans placement velocity stream-lines in basement 1 at impulse fans plane for NPV scenario.

((b)) Optimized jet fans placement velocity stream-lines in Basement 2 at impulse fans plane for NPV Scenario.

Figure 4.3: Optimized jet fans placement velocity streamlines analysis at impulse fans plane for NPV Scenario for (a) basement 1 and (b) basement 2.

Table 4.1: Details of Inflows at Fresh Air Car park Under Study for NPV and EM.

Fresh Air inlets	Inflow/Out flows	Air flows (NPV)(m3/hr)	Air flows (EM)(m3/hr)
FA-11	Inflow	32,180	65,660
FA-12	inflow	58,100	123,550
FA-21	Inflow	50,870	106,200
FA-22	inflow	75,920	158,540

4.1.2 Emergency Pollution Mode

The steady simulation images showed the different aspects of airflow and performance for EM with the following constrains; Iterations of 775, Fluid Cells of 998,324, and Particle Cells of 385,065.

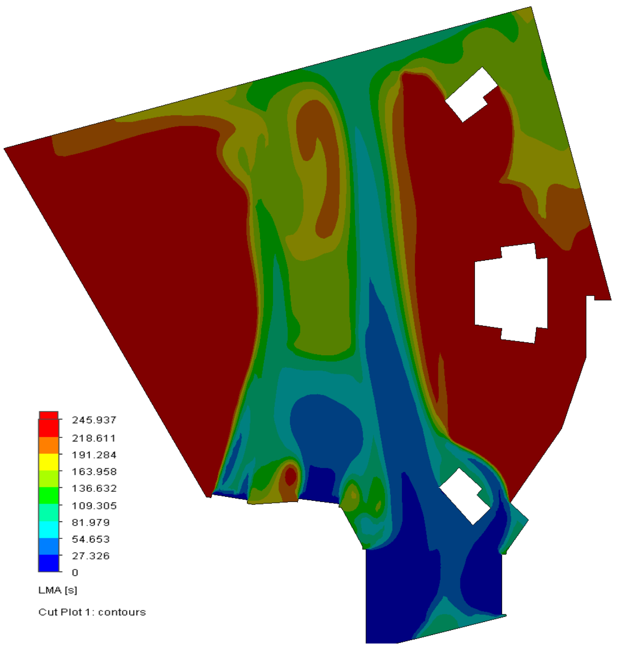
NPV scenario during operation is half the flow rate of EM operation flow rate, hence expected results are the same in terms of air streamlines. Figure 4.3 (a) and Figure 4.3 (b) stream lines shows how air enter car park and how it exits. The simulations also showed the contours and streamlines going through the jet fans in each of the two basements. In addition, the simulation clearly shows how the fresh air inlet values are. The velocity streamlines as shown in Figure 4.3 (a) and Figure 4.3 (b) shows the velocity streamlines during operation in elimination of stagnant areas. This shows about 99% stagnant areas reduction which would have a lot of significance on operation of the systems during fire mode.

4.1.3 CFD Analysis LMA at 1.7 m Plane Level

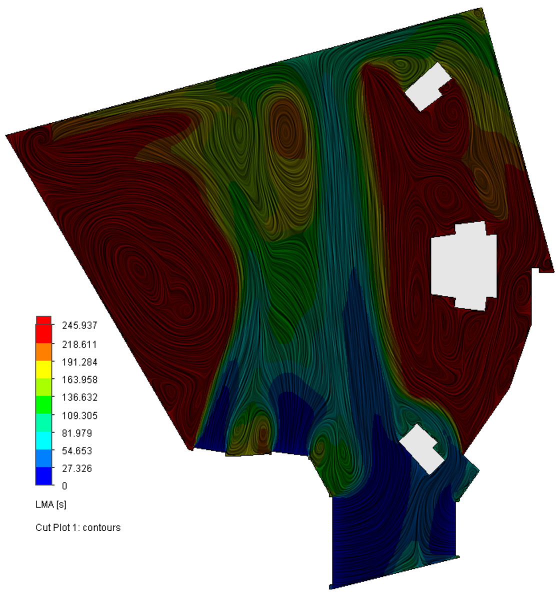
The steady simulations images showed the different aspects of air flow and performance for NPV only with the following constrains; Iterations of 308 , Fluid Cells of 3,783,822, and Particle Cells of 650,065.

Simulation results were obtained for the two car parks under consideration on basement 1 and basement 2. This was for one scenario; Normal pollution ventilation (NPV). The key was analysis of air and concentration with regard to velocity as they show the air distribution at 1.7 m LMA plane level. As shown in Figure 4.4 (a) and Figure 4.5 (b), the velocity field at 1.70 m above the floor plane of each Basement is well depicted. These figures show that there are no significant stagnant air areas in this car park.

As shown in Figure 4.4 (b) and Figure 4.5 (b), the LMA field at 1.70 m above the floor plane of each of the basement some air re-circulation, especially in the central areas of Basement 1, may be observed. This was expected given the boundary conditions and additional restrictions advised in final stages, along with some short-circuit effect in the left area of every level. However, Figure 4.6 (a) and Figure 4.6 (b) show a scale change of this variable in order to verify that this effect is not severe enough to be taken into consideration and acceptable levels of air quality are obtained, especially in Basements 1 and 2.



((a)) Conventional jet fans placement for LMA at plane 1.7 m from basement 1 of the car park for NPV scenario - Scale range.



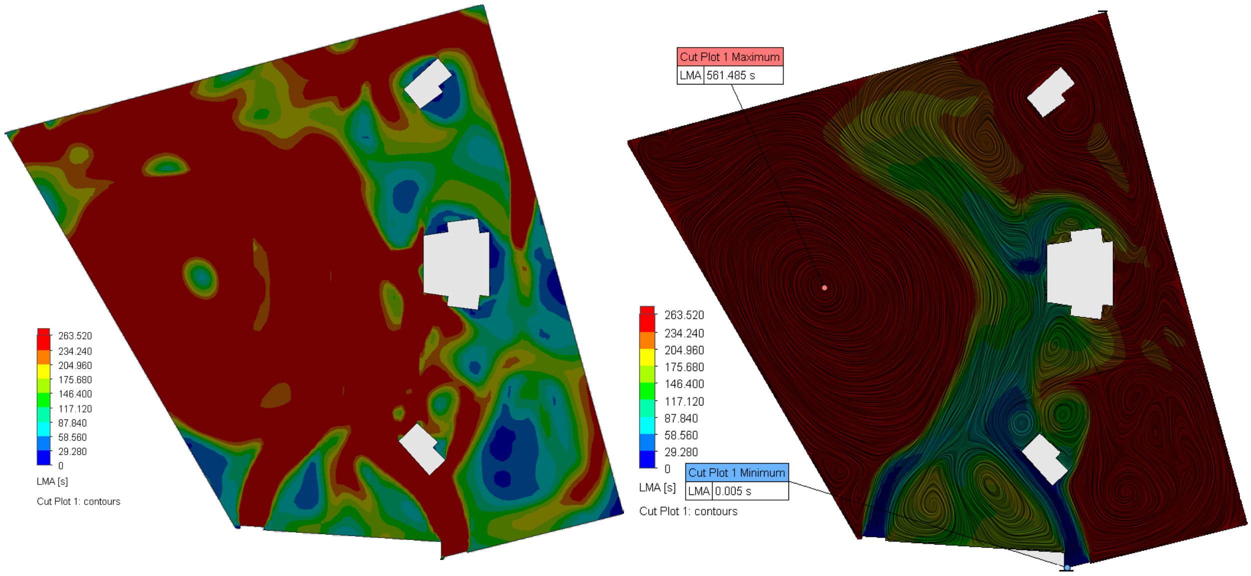
((b)) Optimized jet fans placement for LMA at plane 1.7 m from Basement 1 - scale range.

Figure 4.4: Comparison between convention with optimized placement of jet fans for LMA at plane 1.7 m from basement 1 for NPV scenario - scale range.

The essence of this analysis was to ensure there is no significant stagnation of air at 1.7 m above ground. Air velocity of 0.1 m/s or greater is normally considered desirable. The parameters were then plotted for the jet fan plane contours and their associated streamlines.

4.1.4 LMA at 1.7 m During Normal Pollution Mode

The contours and steam lines in Figure 4.4 (a) and Figure 4.4 (b) shows how air enters the car parks and how it exits. This shows the velocity fields at 1.7 m above the finished floor



((a)) Conventional jet fans placement for LMA at plane 1.7 m from basement 2 of the car park for NPV scenario - scale range.

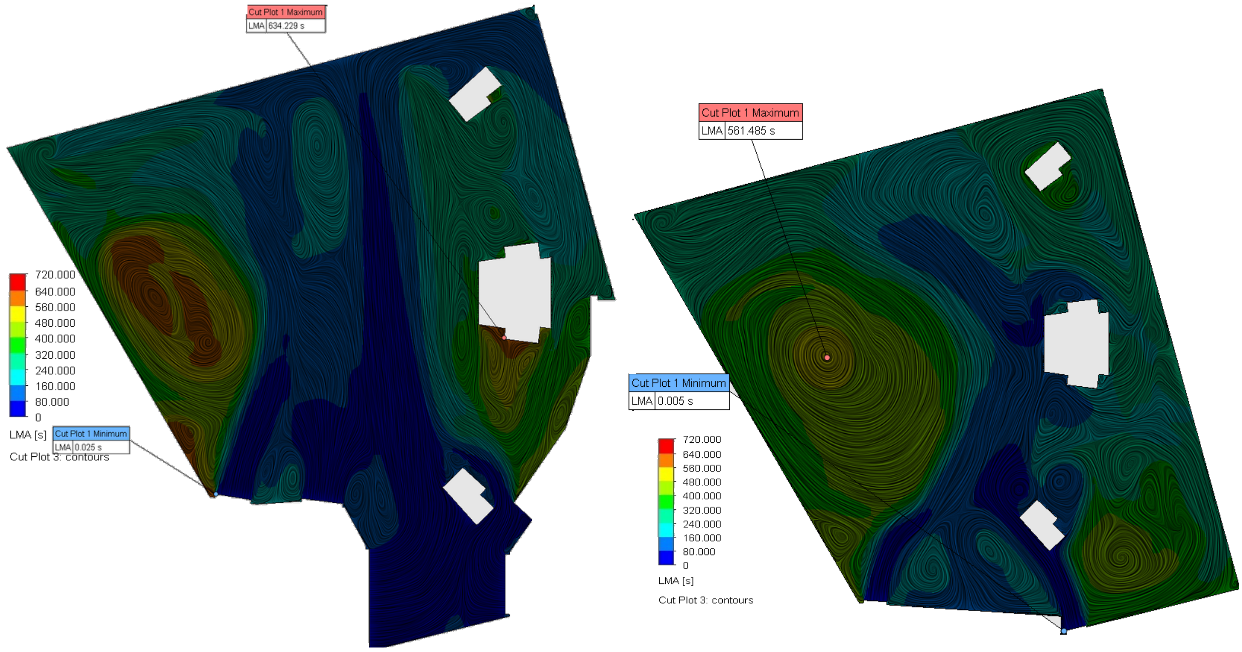
((b)) Optimized jet fans placement for LMA at plane 1.7 m from basement 2 - Scale range.

Figure 4.5: Comparison between convention with optimized placement of jet fans for LMA at plane 1.7 m from basement 2 for NPV scenario - scale range.

level which is the average human height. The minimum LMA is 0.05 s and maximum is 561.485 sec as shown on Figure 4.5 (b) Figure 4.6 (b) for basement 2. The scale ranges in the Figure 4.6 (a) and Figure 4.6 (b) ranges was NPV circulation at 5 ACH (720 Secs). Zero velocity (0) has dark blue colouration meaning stagnation of air; hence, no re-circulation. Since 0.1 m/s is considered desirable, therefore in Figure 4.5 (b) and Figure 4.6 (b) it is evident there is a lot of reduction of stagnant air at LMA Plane. The velocity streamlines as shown in Figure 4.6 (a) and Figure 4.6 (b) shows the velocity streamlines during operation in after elimination of stagnant areas. This shows about 99% stagnant areas reduction at 1.7 m LMA plane which would have a lot of significance on the operation of these systems.

4.2 Jet Fans Placement Optimization

The summary of the relationship between the rule of thumbs and optimal placement is as shown in Table 4.3. The initial approximate capacity and number of jet fans was achieved using the rule of thumb on floor layout shown in Figure 3.1 and Figure A.1. This was done according to Figure 2.3 which considered jet fans not to be placed more than 15 m apart on sideways and not more than 30 m apart in terms of through distance. It is evident that



((a)) Convention jet fans placement for LMA at plane 1.7 m from basement 1 of the car park for NPV sce-nario.

((b)) Convection jet fans placement for LMA at plane 1.7 m from basement 2 of the car park for NPV sce-nario

Figure 4.6: Representation for convention jet fans placement consideration for LMA at plane 1.7 m for basement 1 and 2.

the optimization has reduced the number of jet fans by 5, with 25 N-A jet fan having 3 less and the 50 N-C having 2 less installed. This could lead to a monetary during acquiring of the jet fans.

Table 4.2: Summary of Optimized and Rule of Thumb Jet Fans Comparison.

Level	50N-Centrifugal Jet fans (No)	25N-Axial jet fans (No)
Basement -1	5	4
Basement -2	8	4

The optimization results done for both Basement 1 and 2 and the results obtained are summarized in Table 4.2. For basement 2 the number of jet fans are many because the area of coverage was bigger compared to basement 1. The summary relationship of the rule of thumbs and optimal placement is shown in Table 4.3.

Table 4.3: Summary of Jet Fans Placement Based on Rule of Thumb and Optimal Compar-ison.

Method	Level	Jet fans type	Quantity	Total
Rule of thumb	Basement-1	25N-A	6	26
		50N-C	9	
	Basement-2	25N-A	5	
		50N-C	6	
Optimal Placement	Basement-1	25N-A	4	21
		50N-C	5	
	Basement-2	25N-A	4	
		50N-C	8	

4.3 Experimental Validation

4.3.1 Experimental Set up for Dead Zones

Figure 4.8 shows the relationship of carbon monoxide concentration in regards to the time of the movements of cars in the two basement car parks. It is evident that after 5 minutes interval, the concentration went upwards on driving the cars at the two basements. At the 20^{th} minute, the CO went up to the record of 170 ppm and 87 ppm for basement 2 and basement 1 respectively. On putting ON the jet fans the concentration dropped. This was for the most probable stagnant areas as shown in Figure 4.1 (b) and Figure 4.2(b) with dark blue areas with almost zero velocity according to scale range of CFD simulation. The measurement points for the Velocity (B11 to B22) and CO concentration are shown in Figure 4.7 and Figure 4.10. By the end of the 35^{th} minutes, the CO concentration had dropped to 45 ppm and 15 ppm.

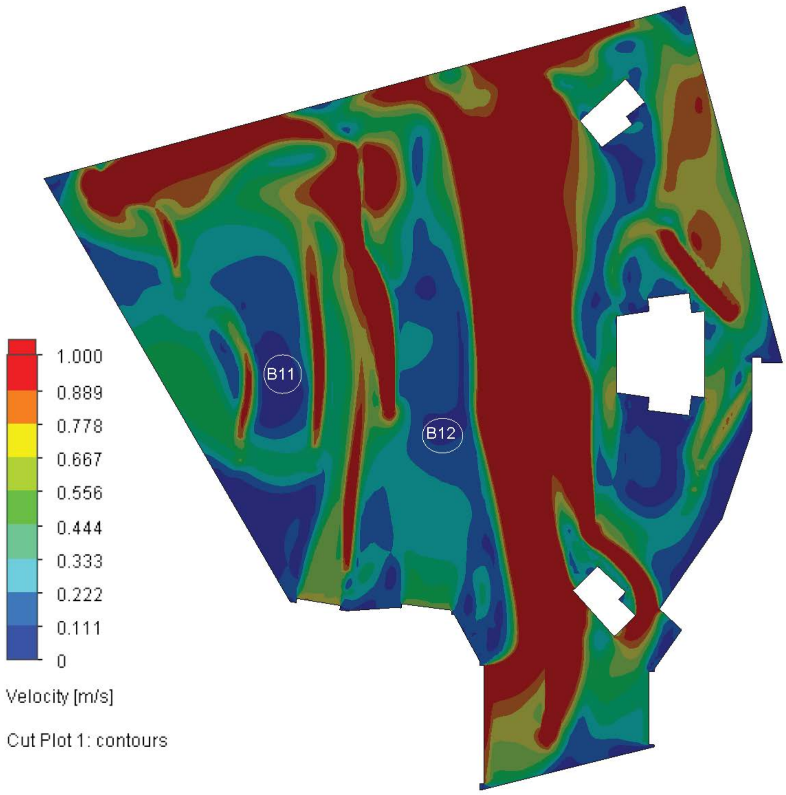


Figure 4.7: Velocity and Carbon monoxide measurement points for Basement 1.

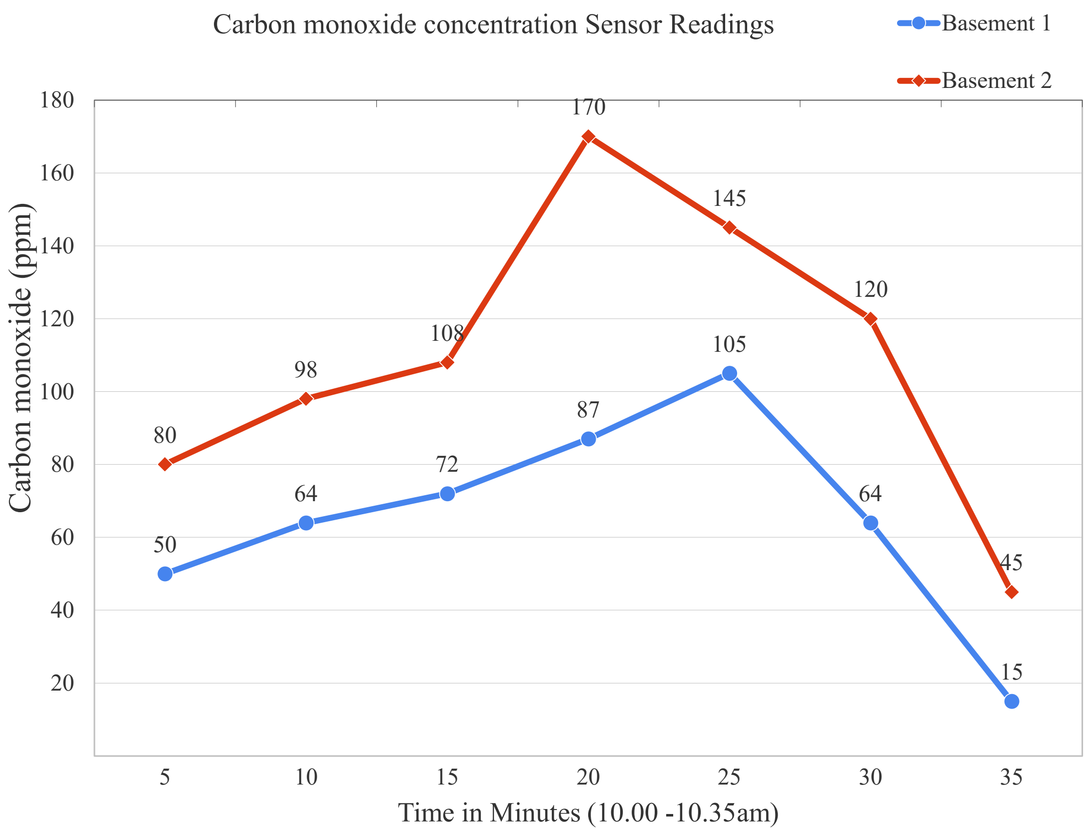


Figure 4.8: Carbon monoxide concentration sensor readings.

According to the UK standard as per Table 1.1, it is stipulated that for an average period of 8 hrs and 15 minutes, the maximum carbon monoxide exposure recommended should be 50 ppm and 300 ppm respectively. During the experiment for the 15 minutes; from the time the jet fans were actuated at 20th to 35th minute as shown in Figure 4.8, the CO concentration dropped to 45 ppm hence below the 300 ppm threshold. It is also evident that with a span of 8 hrs, the CO concentration would be below 50 ppm as the jet fans work to dilute the CO concentration. With such results on these areas with the most probable dead zone points, it was concluded that the dead zones had been eliminated entirely in the car park and at the same time conforming to the UK standard which the research objective was based. The results of the velocity of the measurement points are shown in Table 4.4 and shown in graphical representation in Figure 4.9. From the experimental results, it is evident the CO concentration levels were able to modulate according to Table 3.4 on the operation of jet fans. The experimental velocities range were 0.11 m/s, 0.19 m/s, 0.32 m/s and 0.19 m/s for B11, B12, B21 and B22 points respectively. The International Standard recommends desirable velocity of 0.1 m/s and above in a car park for consideration to be no stagnation of air or no dead zones.

Table 4.4: Measurements Points for Velocity in the Car park Under Study on Normal Pollu-tion Mode.

Measurement points	B11	B12	B21	B22
Measured Velocity (m/s)	0.11	0.19	0.32	0.19
Simulated Velocity max range (m/s)	0.111	0.111	0.444	0.222

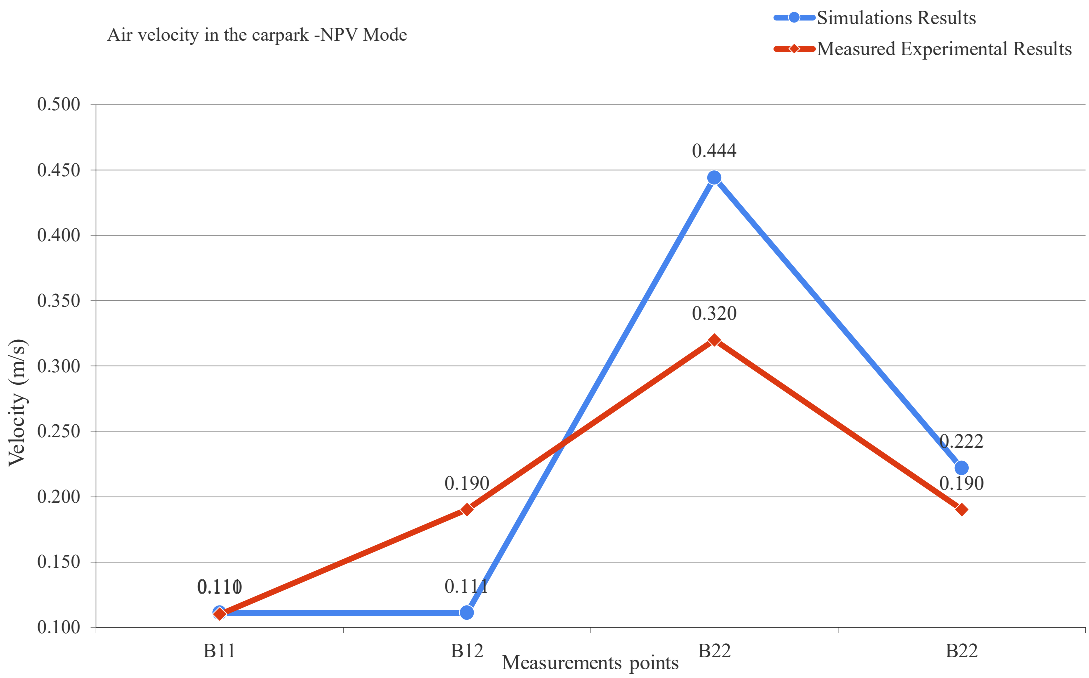


Figure 4.9: Comparison of experimental validation velocity measurements with simulation values.

4.3.2 Experimental Airflow Analysis for the Actual Car Park Set up

In this section, analysis of measured flow values using air flow meter was done on the site under case study. This was done for both ventilation scenarios. Air flows were measured for basement 2 at the Driveway points (DR-1 to DR-3) for Emergency ventilation scenario with measurement points as shown in Figure 4.10. All the fans; main extraction fans and jet fans were run. The fresh air in flow results were obtained where initially these areas had been considered to be environmental pressures areas points. The results obtained were tabulated as shown in Table 4.5 and Table 4.7 in comparison with simulation results for both the NPV and EM modes respectively. As shown in Table 4.5 and represented graphically in Figure 4.11, the representations show that the Fresh air inlets (FA-11) to (FA-22) obtained from the experiment are 20% lower than the simulation results for EM mode.

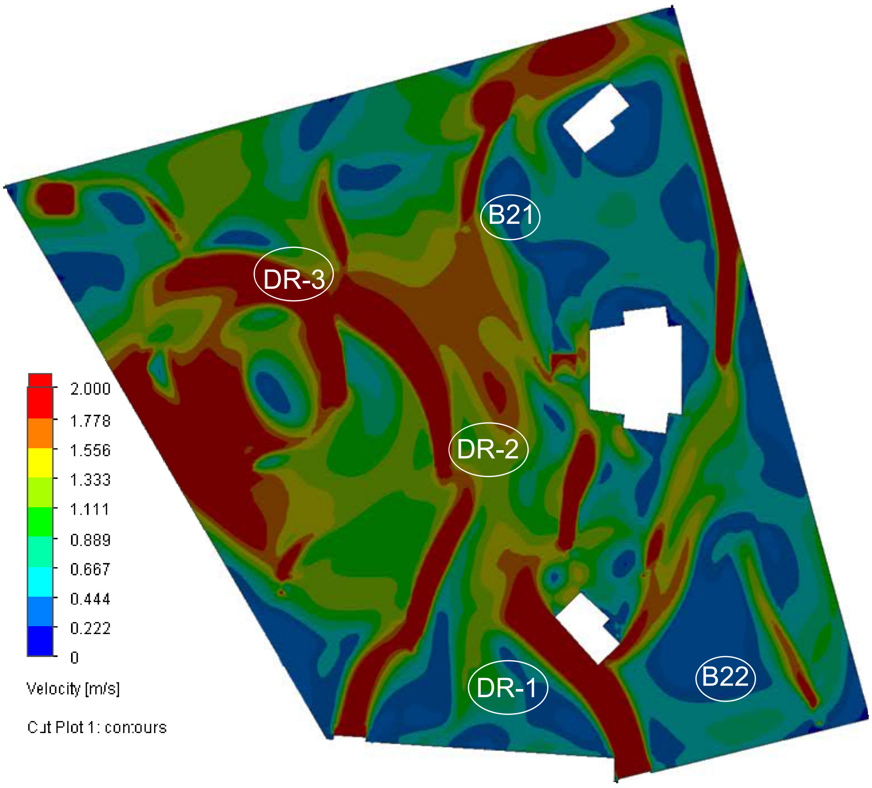


Figure 4.10: Velocity and carbon monoxide measurement points for basement 2.

As indicated in Table 4.6 and Figure 4.12, the Airflow points (DR-1), (DR-2), and (DR-3) obtained from the experiment are 23% lower than the simulation results EM mode.

Table 4.5: Inflows at Fresh Air Car park Under Study for Emergency Pollution Mode.

Fresh Air inlets	**Air flows (Simulation results)(m^3/hr)**	**Air flows (Measured results)(m^3/hr)**
FA-11	65,660	55,150
FA-12	123,550	90,900
FA-21	106,200	89,530
FA-22	158,540	123,340

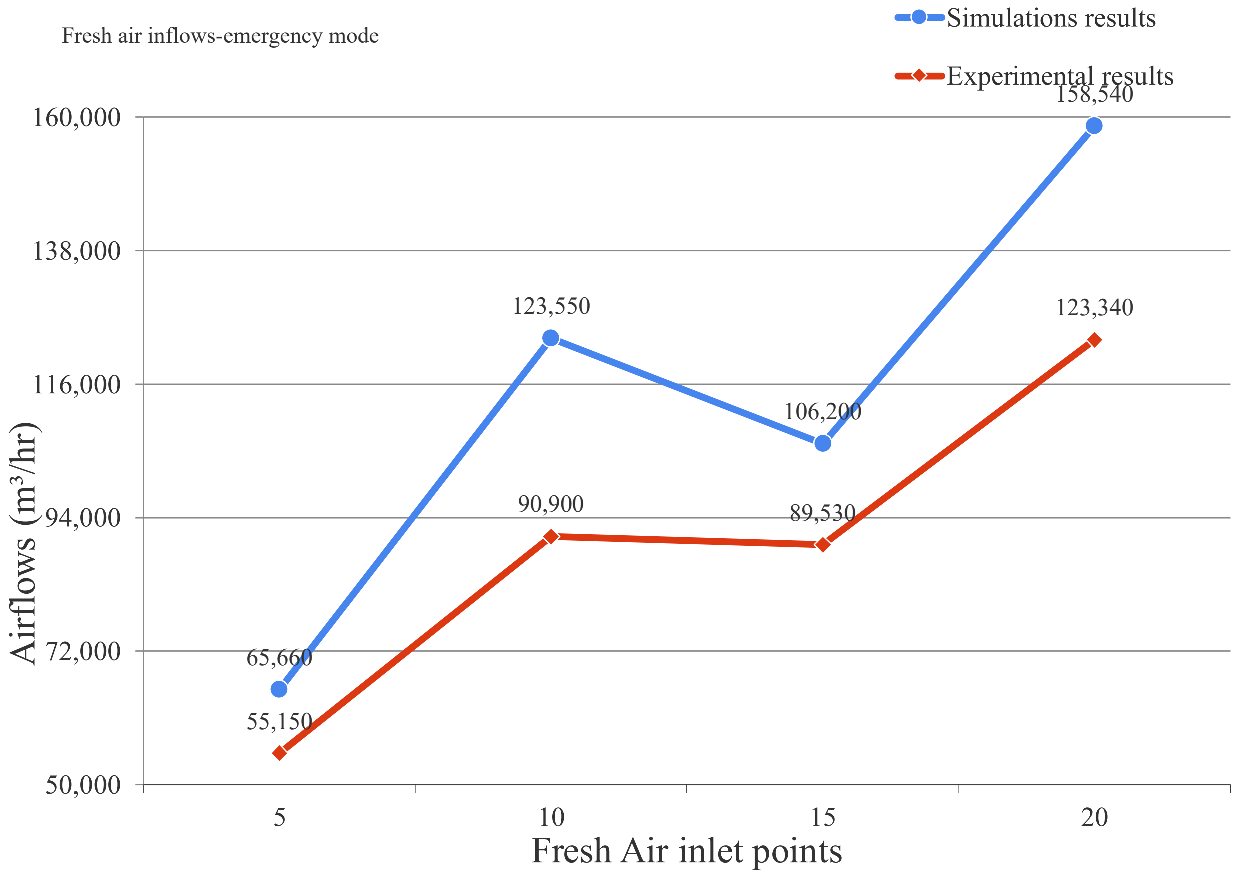


Figure 4.11: Comparison of air flows for Simulations and experiment for the fresh air inlets. Table 4.6: Velocity for Air on Driveway at Selected Points in the Car park Under Study on Emergency Mode.

Air flow points	Air flows (Simulation results)(m/s)	Air flows (Measured results)(m/s)
DR-1	1.093	1.231
DR-2	2.045	3.653
DR-3	2.631	4.020

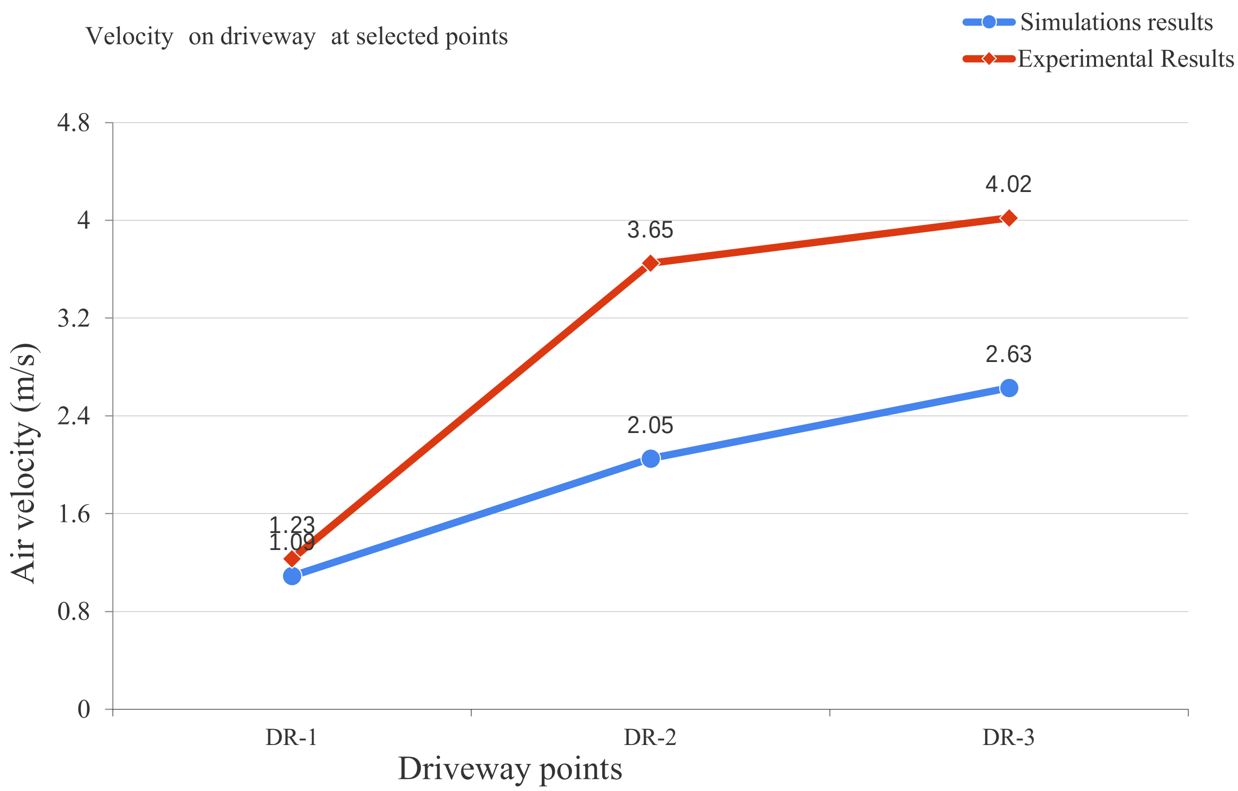


Figure 4.12: Comparison of air of the simulations and experiment air flows for the driveway points.

4.3.3 Experimental LMA at 1.7 m Plane Results Analysis Validation

In this section, an analysis of measured flow values using an airflow meter was done on the site under the case study. This was done for the NPV ventilation scenario only. All the fans, main extraction fans, and jet fans were run at half speed. The fresh air in flow results were obtained where initially these areas had been considered to be environmental pressure areas points. The results obtained were tabulated as shown in Table 4.7 and Table 4.8 in comparison with simulation results for the NPV mode only. As shown in Table 4.7, the Fresh air inlets (FA-11) to (FA-22) obtained from the experiment are 19% lower than the simulation results. Three other separate airflows were measured for each of the basements at the driveway points (DR-1, DR-2, and DR-3) for the two basements for both ventilation scenarios. The air velocity ranges from 0.52 to 1.22 (m/s) and 0.58 to 1.79 (m/s) for the simulation and measured results, respectively. The lower velocities are attributed on the side with natural fresh air intake while the higher are near the main extract fans. As shown in

Figure 4.13, the airflow points (DR-1), (DR-2), and (DR-3) obtained from the experiment are 22% lower than the simulation results.

Table 4.7: Inflows at Fresh Air Car park Under Study for Normal Pollution Mode.

Fresh Air inlets	Air flows (Simulation results)(m^3/hr)	Air flows (Measured results)(m^3/hr)
FA-11	32,820	27,575
FA-12	61,775	45,450
FA-21	53,100	44,765
FA-22	79,270	61,670

Table 4.8: Velocity for Air on Drive-way at Selected Points in the Car park Under Study on Normal Pollution Mode.

Air flow points	Air flows (Simulation results)(m/s)	Air flows (Measured results)(m/s)
DR-1	0.52	0.58
DR-2	0.97	1.71
DR-3	1.22	1.79

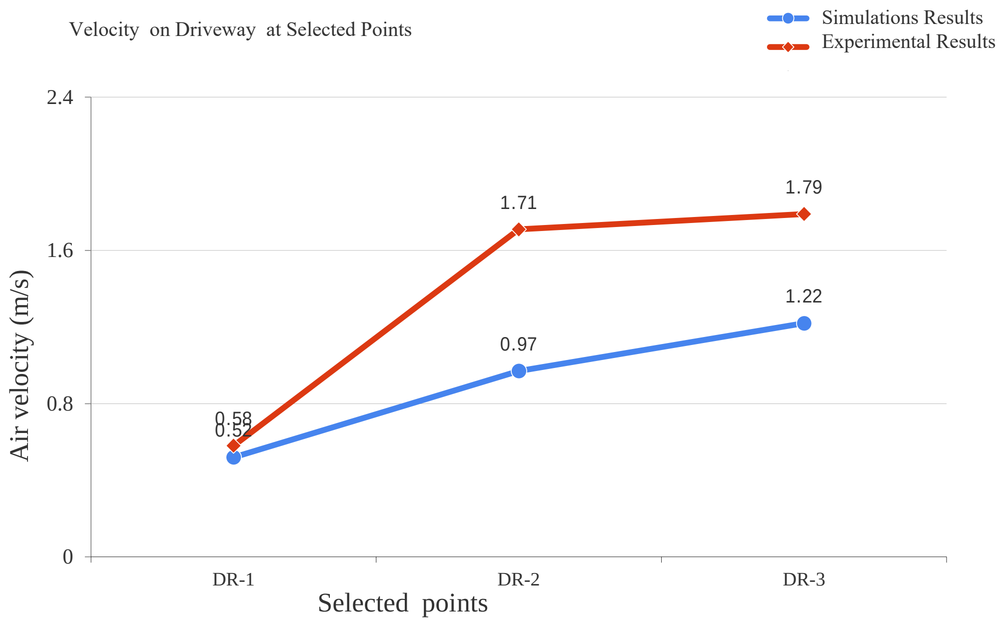


Figure 4.13: Comparison of the simulations and experimental air flows for the driveway points.

4.4 Discussions

In the first experiment in subsection 4.3.1, validation experimental for dead zones elimination was carried out by creating a polluted environment and then checking the response of the CO sensor nearby. This was to help achieve the intended purpose of ensuring there was no dead zones for a safe environment during NPV ventilation and evacuation during fire fighting on EM mode. The concentration dropped to 45 ppm for basement 2 and 15 ppm for basement 1 respectively, as shown in Figure 4.8. The results have indicated that there was indeed elimination of dead zones since the experiment was conducted on the most feasible areas. Similarly in order to validate safe evacuation during NPV mode with no air stagnation, measurements were taken on the samples of probable stagnant areas. The results from experiment are as shown on Figure 4.9 which have indicated that the operation of jet fans velocity in the most stagnant areas was above the recorded desirable velocity of above 0.1 m/s hence no air stagnation. In conclusion, its evident that the dead zones were completely eliminated and at the same time air quality and recommended velocity achieved in the validation experiment.

The second simulation experiment in subsection 4.3.2, focused on the experimental air flows for the actual car park. The results recorded relatively close similarity between the simulations and measured result throughout. As shown in Table 4.5 and Table 4.6 there was very little difference. This minimal difference could be attribute the fact that fans performance have curve optimal relationship between absorbed power and airflow relationship range. This ranges leads to the slight different as power consumption drawn is a function of flow rate. It was therefore concluded that the experiment had a positive affirmation that the required flow rate during NPV and EM was achieved.

The third simulation experiment in subsection 4.3.3, was on airflow's analysis on LMA at 1.7 m human height for the actual car park was set out. The results recorded relatively similarity between the simulations and measured results. As shown in Table 4.7 and Table 4.8 there was a very little variance of less than 10%. This minimal difference could be attributed by the fact that fans performance have curve optimal relationship between absorbed power and volumetric flow relationship range. It was therefore concluded that the experiment achieved the desired results of required flow rate during NPV at 1.7 m LMA height.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The primary contribution of this research was to remove dead zones as result of obstructions in car park designs before implementation. In this regard, daily emissions in a car park control pollution, and smoke control aim in a car park functionality during need were ascertained. The 3D computer CAD model for a car park was developed representing the computer graphics and gave meshes and visualization as well as representation of the actual complex facility for further analysis. This approach will help designers and clients in a detailed analysis of the entire car park on CFD analysis by identifying the dead zone caused by obstructions and air quality at 1.7 M LMA height. The results showed that the pro-posed 3D surface CAD model enhanced the modeling of the entire car park as opposed to the traditional probabilistic scenario while saving time and reliability as well as improving efficiency.

According to analysis, the dead zones were entirely eliminated. This research outcome showed a better analysis method approach for eliminating dead zones or stagnant air for a car park with obstruction down stand beams. The results showed that the proposed simulations done at specific most probable locations at the beam cavities enhanced the modeling of the entire car park as opposed to the traditional assumption of a flat surface and ducted extraction scenario while also saving time and reliability as well as efficiency. Design without any stagnant areas will be of critical importance in providing safety in case of fire to occupants by slowing down its effect, resulting in the safe evacuation of cars parks thus avoiding loss of property or death. Consequently, the research dead zones elimination investment is worthwhile in car parks.

According to the analysis, the jet fans placement optimization was a success. The jet fans placement optimization revealed from the research case study had the potential of saving compared with a conventional method. This was achieved by the fact that the numbers of jet fans reduced from 26 in a convectional method of rule of thumb to 21. The savings ought to be more but the research only considered the costs of jet fans only whereas there are other cost such as cables and panel accessories associated with the IVS system.

This research presented a novel approach for eliminating stagnant air for a car park with obstruction down stand beams LMA at 1.7 m Height. The research analysis and findings outcome showed achievement of air quality at LMA height as simulations and experiments demonstrated desirable air velocity. The results showed that the proposed simulations placed at specific locations at the beam cavities enhanced the modeling of the entire car park as opposed to the traditional assumption of a flat surface and ducted extraction scenario while also saving time and reliability as well as efficiency. Design without any stagnant areas will be of critical importance in providing safety in case of fire to occupants by slowing down its effect, resulting in the safe evacuation of car parks thus avoiding loss of property or death by ensuring considerable airflow at 1.7 m LMA height.

According to analysis, the experiment's validation were successful. It was evident in the research case study by driving a group of cars in the car park hence with stagnant air elimination as per international standard which recommends desirable velocity of 0.1 m/s and above in a car park. This is for consideration for having no stagnation of air or no dead zones with measurements values similar to simulated velocity values. Additionally, the flow velocities in the drive ways selected point values were almost similar to simulation results.

Based on the Modeling tool and methodology used in the research, a better design that is easily researchers and end users was obtained, proving the efficiency of modern computing and operations as opposed to traditional methods of design of car parks.

5.2 Recommendations

It is recommended that future research work should be geared towards further improvement of the demand controller systems of the IVS system in order to save further energy and as well quantify and monetize the associated value. The research further recommends the adoption of the to-be-used car parks analysis and optimized jet fan's placements as this will have massive reaping in savings by the Car park facilities owners, users, designers, and the Fire departments authorities and smart city developers.

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APPENDICES

Appendix I: Floor Layouts

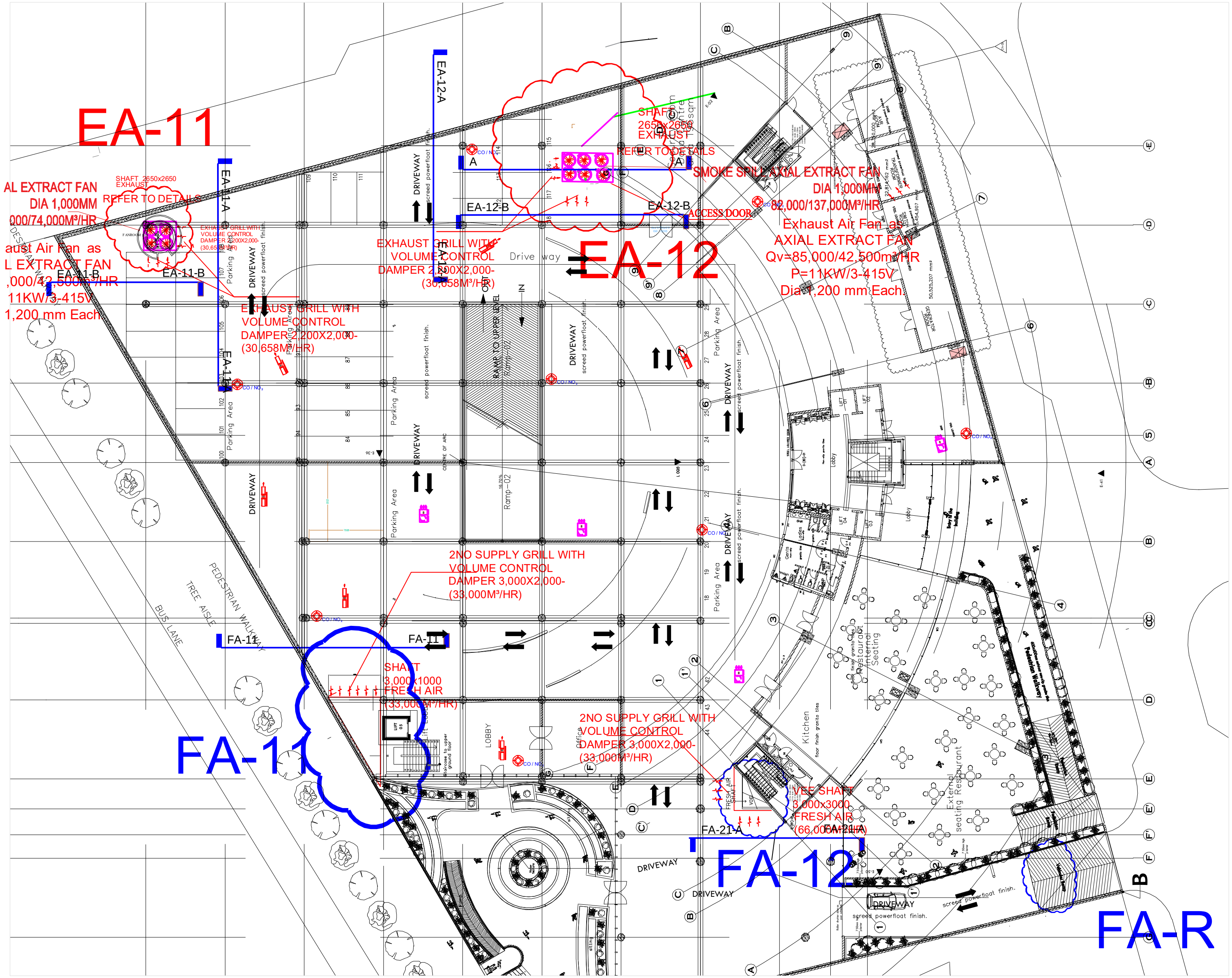

Figure 0.1: Basement 1 for Car Park of the Case Study

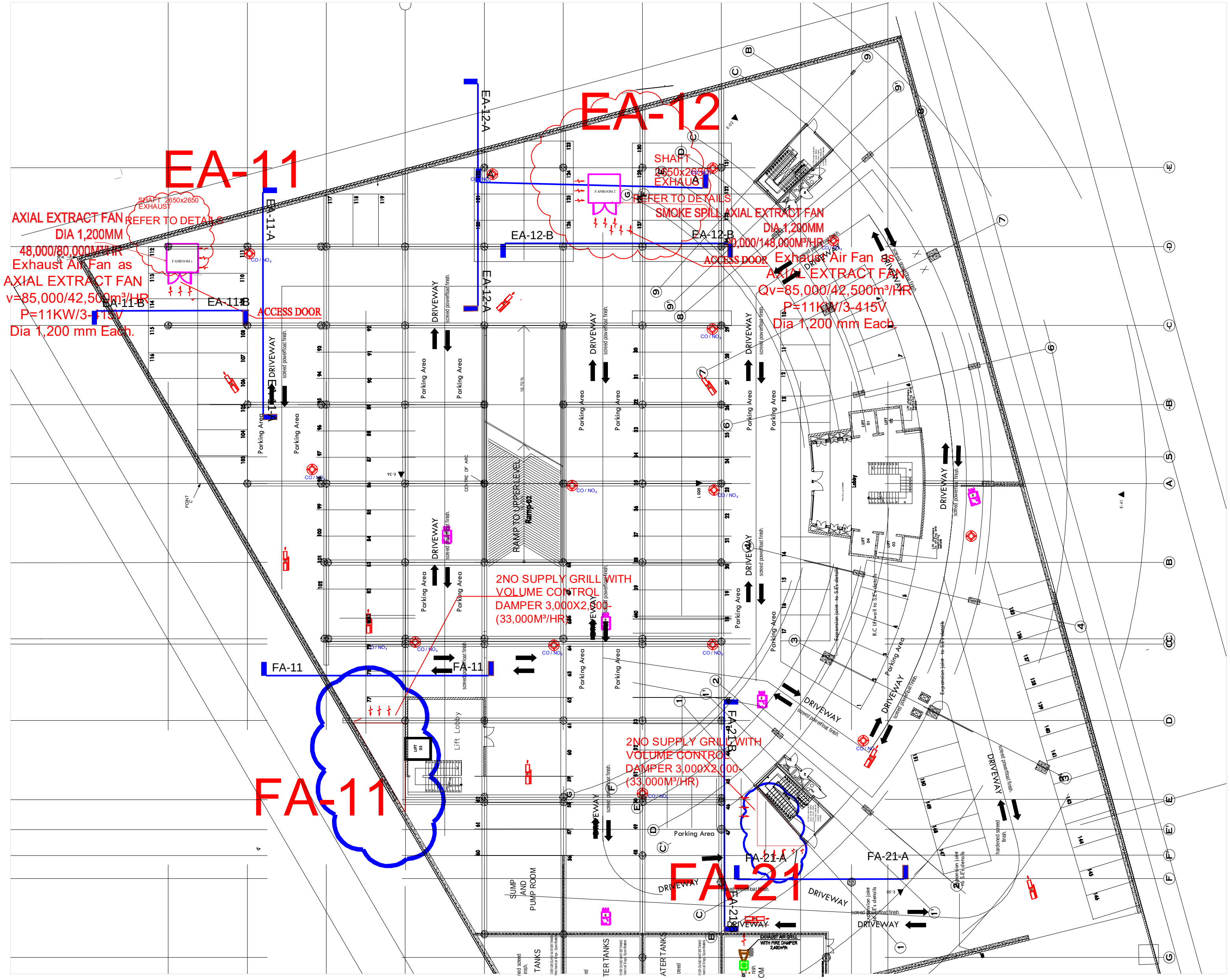

Figure 0.2: Basement 2 for Car Park of the Case Study

Appendix II: 3D Modelling

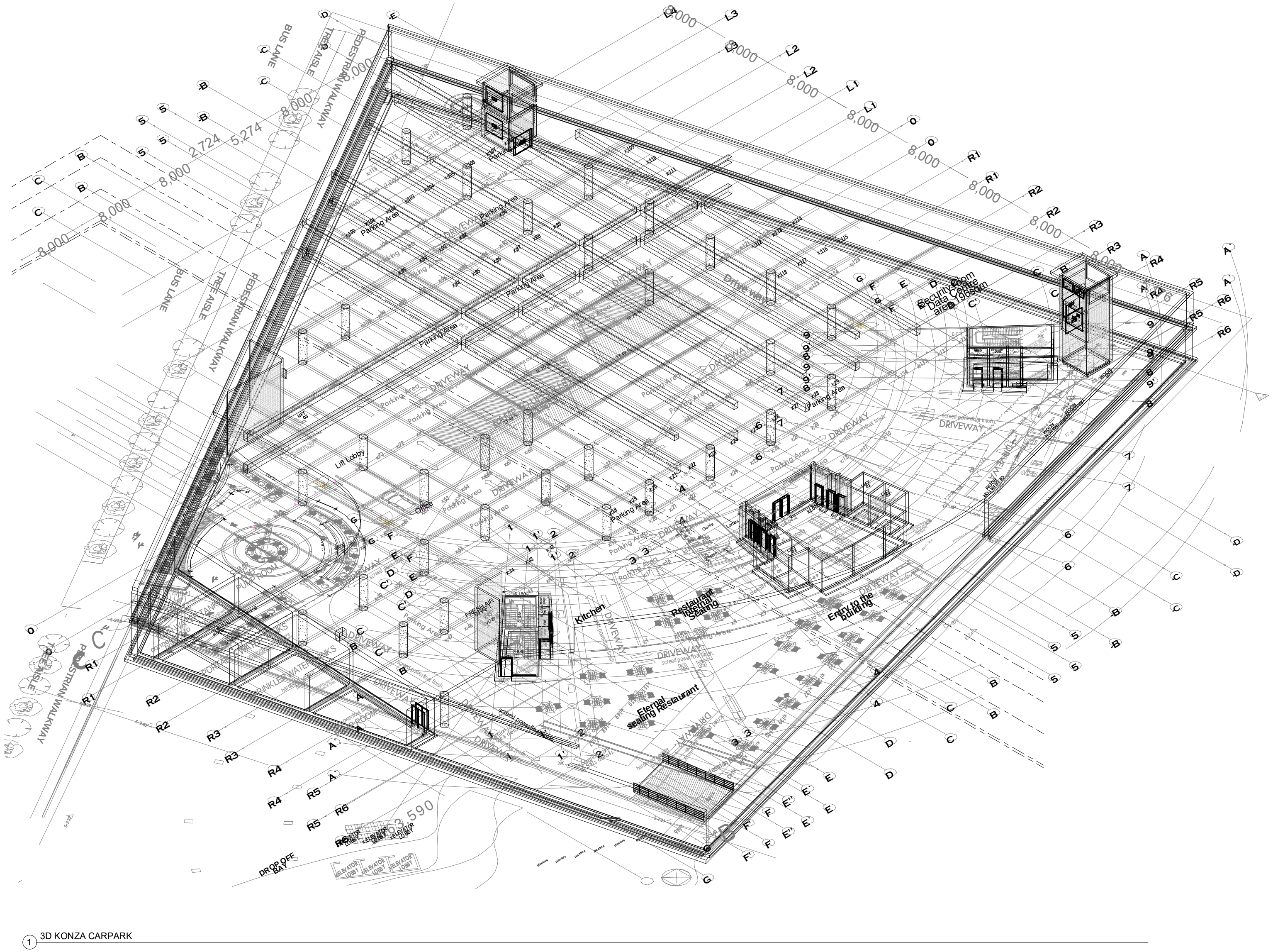

Figure 0.3: 3D Wireframe for two (2) Basements of Car Park Models Developed.

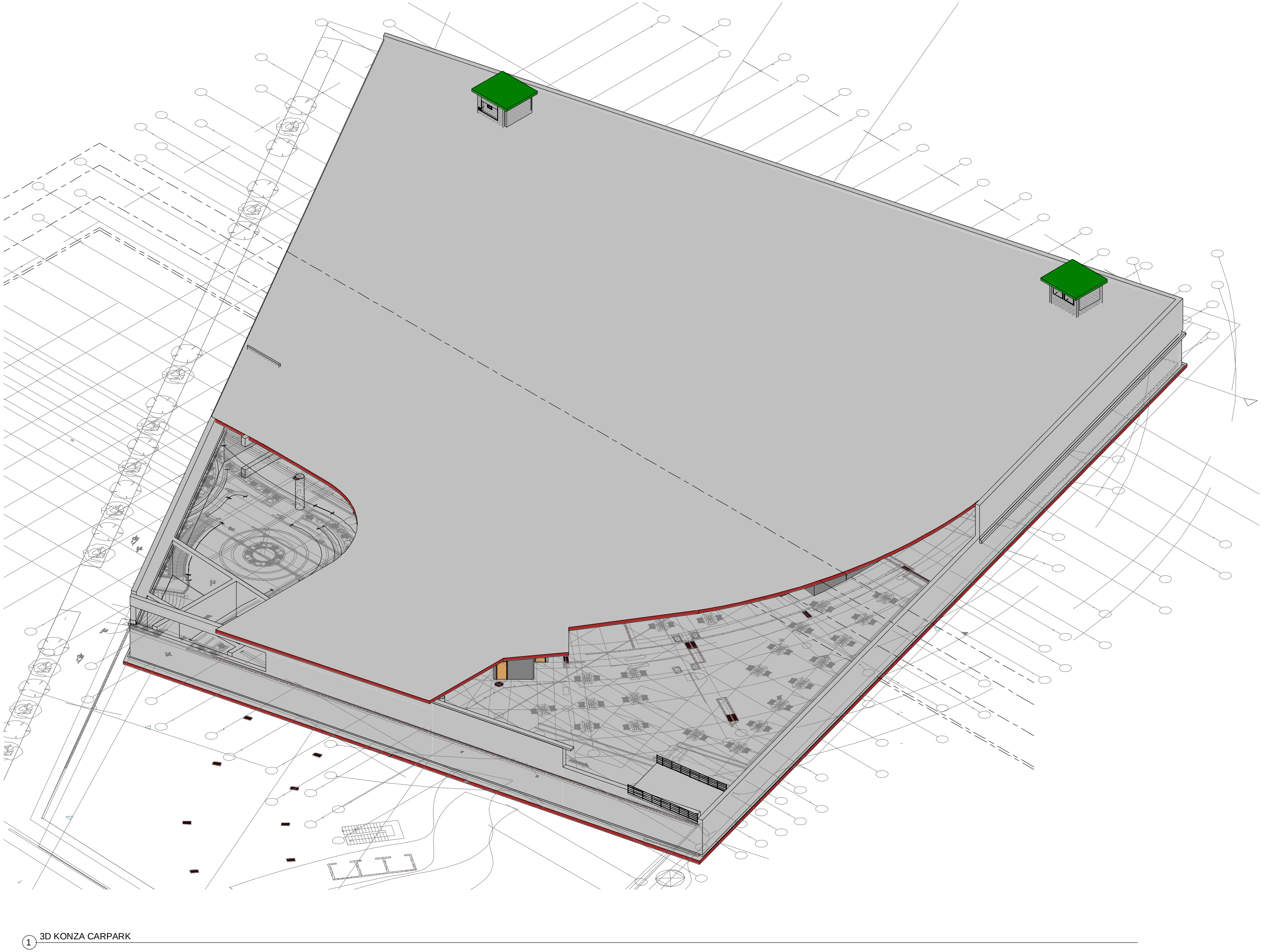

Figure 0.4: 3D realistic coloured model for two (2) basements of car park developed.

Appendix III: Jet Fans

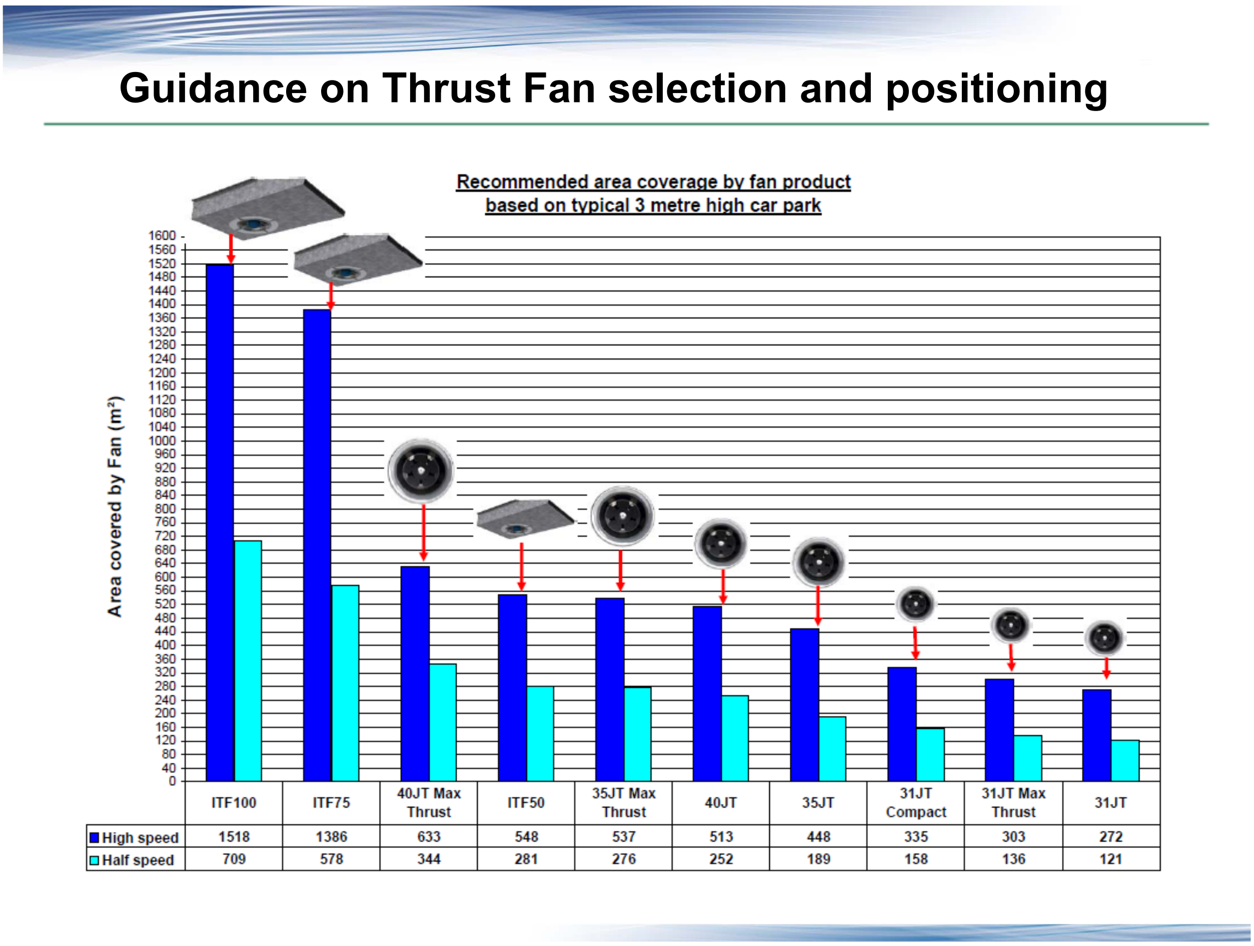

Figure 0.5: Jet fans area of coverage selection and positioning thrust guidance (Palau, 2013).

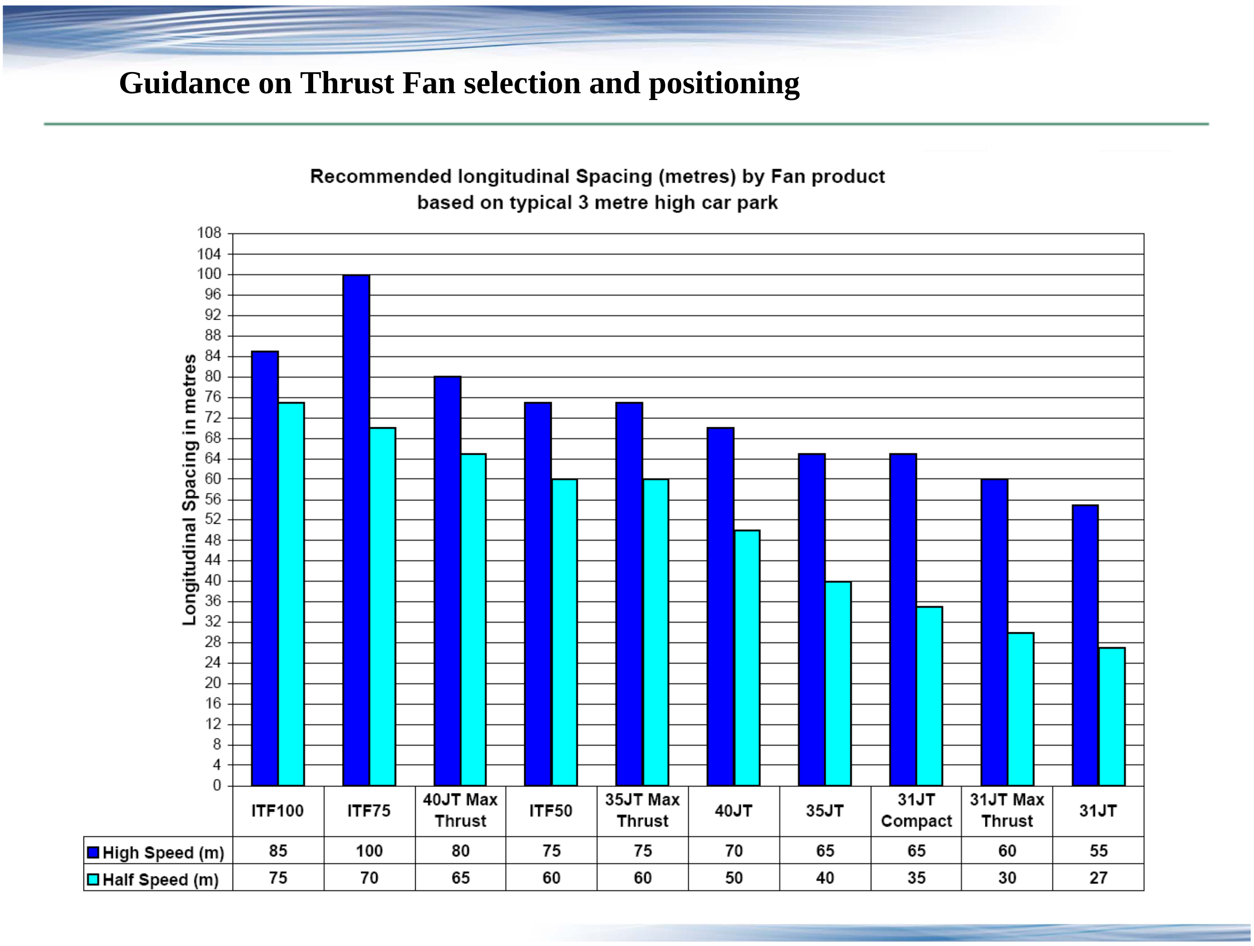

Figure 0.6: Jet fans longitudinal spacing selection and positioning thrust guidance. (Palau, 2013)

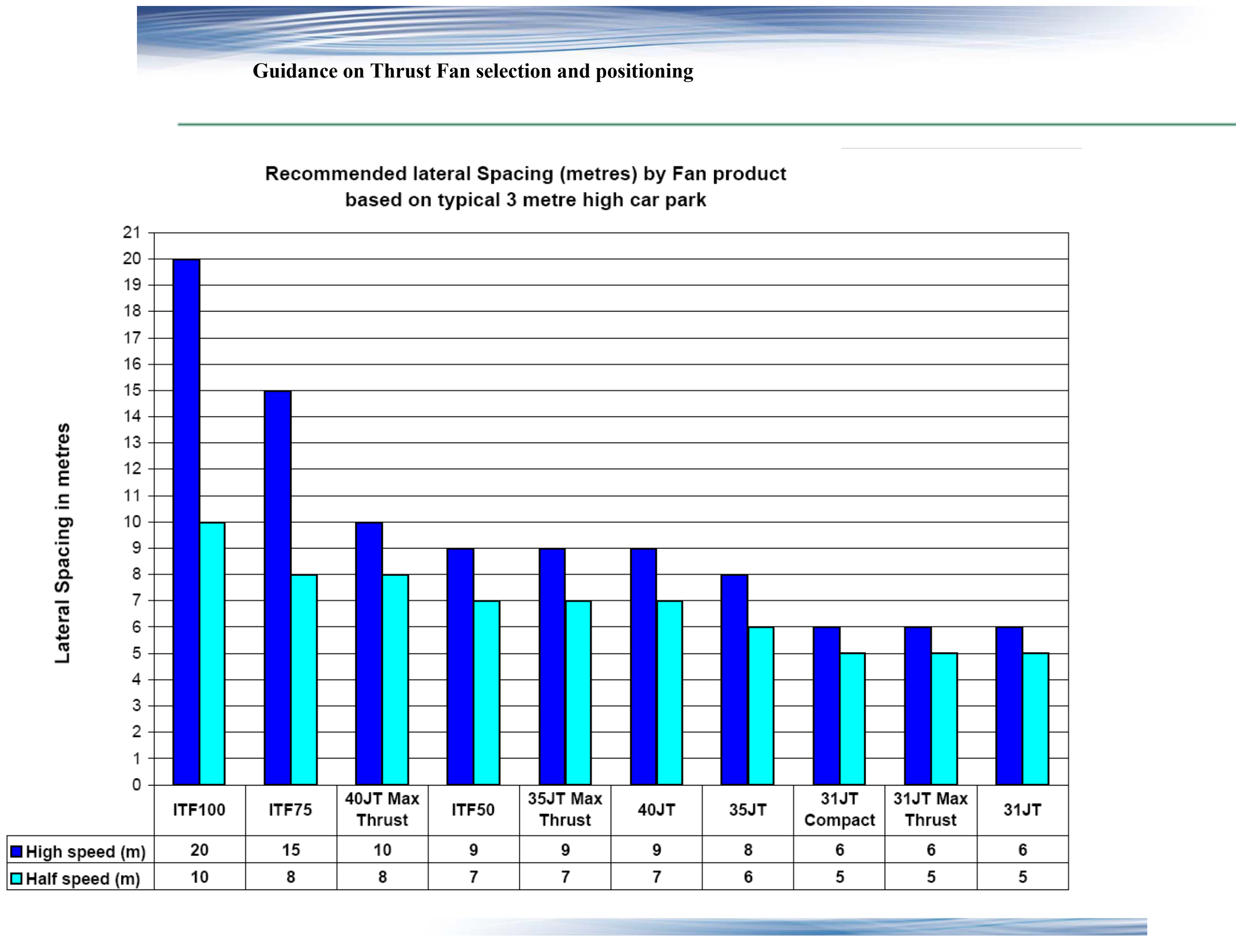

Figure 0.7: Jet fans lateral spacing selection and positioning thrust guidance. (Palau, 2013)