INVESTIGATION AND SIMULATION ON TRANSMISSION, EMERSION AND DISPERSION OF DUST PARTICLE FROM POINT OF GENERATION

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FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
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ABSTRACT

Wood dust is one of the world's oldest and most prevalent occupational hazards. The current studies examine at the impact of lifetime exposure to wood dust in various occupational situations on the risk of lung cancer. In this work, the investigation on occupational safety and health in wood furniture manufacturing sectors from one factory is reported. Computational Fluid Dynamics (CFD) has now made it possible to simulate the airflow behavior using simulation applications. Knowing how the fresh air circulates within a building, around the people inside, and through its openings is crucial to improve air quality. Therefore, the purpose of this study was to use CFD to examine the air flow characteristics in a wood furniture industry. In this study, the flow was assumed to be a steady-state, incompressible, and two-dimensional turbulent flow. A standard k-epsilon turbulent model was applied to show more accurate and reasonable result. A CFD software was used to perform the numerical simulation. The simulation model of wood furniture factory was constructed with one inlet and three outlets where two opening outlets located on the top side wall while the main outlet located at the end of the factory. For the simulation model, the average air speed at the inlet was 5 $m \cdot s^{-1}$ by considering the average wind speed in our country and the speed from the fan available inside the factory. For validation of simulation model, the air quality data of particulate matter which refers to wood dust obtained from five different station are compared to the permissible exposure limit (PEL) according to the Department of Occupational Safety and Health (DOSH). The level of particulate matter pollutants are collected from several locations to identify the sources of respiratory hazards using the air quality monitor devices. The findings revealed that the sources of dangers changed depending on the workstation's purpose. Finally, two modifications are proposed on the original layout of factory to reduce the dust particle inside the factory: (1) Modification on the size of inlet and main outlet; (2) Modification on the location of inlet and main outlet. Three situations were simulated for each category of modification to predict the airflow pattern in the investigated factory. Result suggest that both inlet and outlet need to have a similar size for a smooth flow of air and the location of the outlet need to change into the middle at the end of factory in order to reduce the zero-velocity area. An addition of inlet in one of the stations are also proposed for a better result.

Keywords: Wood dust, Air flow, Computational fluid dynamic (CFD), Particulate matter (PM), Furniture industry.

PENYIASATAN DAN SIMULASI BERKAITAN PENGHANTARAN, PELEPASAN DAN PENYEBARAN ZARAH HABUK DARI SUMBER PENJANAAN

ABSTRAK

Habuk kayu adalah merupakan salah satu ancaman yang tertua dan paling lazim berlaku dalam sektor pekerjaan. Kajian semasa mengkaji kesan pendedahan seumur hidup kepada habuk kayu dalam pelbagai situasi pekerjaan terhadap risiko kanser paru-paru. Dalam kajian ini, penyiasatan mengenai keselamatan dan kesihatan pekerjaan dalam sektor pembuatan perabot kayu daripada satu kilang dicatatkan. Pengiraan dinamik bendalir hari ini membolehkan untuk mensimulasikan tingkah laku pergerakan udara menggunakan aplikasi simulasi. Mengetahui bagaimana udara segar bergerak dalam bangunan, di sekeliling orang di dalam dan melalui bukaan adalah penting untuk meningkatkan kualiti udara. Oleh itu tujuan kajian ini adalah untuk menggunakan CFD untuk mengkaji ciri pergerakan udara dalam industri perabot kayu. Dalam penyiasatan ini, pergerakan udara telah dianggap sebagai aliran stabil, tidak boleh mampat dan dalam keadaan dua dimensi aliran tidak teratur. Model standard turbulen k-epsilon telah digunakan untuk menunjukkan hasil yang lebih tepat dan munasabah. Perisian CFD telah digunakan untuk melakukan simulasi berangka. Model simulasi kilang perabot kayu dibina dengan satu bukaan masuk dan tiga bukaan keluar di mana dua bukaan terletak di dinding sebelah atas sisi kilang manakala bukaan keluar utama terletak di hujung kilang. Bagi model simulasi, purata kelajuan udara di salur masuk ialah 5 $m \cdot s^{-1}$ dengan mengambil kira purata kelajuan angin di negara kita dan kelajuan dari kipas yang terdapat di dalam kilang. Bagi pengesahan untuk simulasi yang dilakukan ke atas model, data kualiti udara bahan zarah dan juga merujuk kepada habuk kayu yang diperoleh daripada lima stesen berbeza dibandingkan dengan had pendedahan yang dibenarkan (PEL) mengikut Jabatan Keselamatan dan Kesihatan Pekerjaan (DOSH). Tahap bahan zarah yang memberi pencemaran dikumpulkan dari beberapa lokasi untuk mengenal pasti punca bahaya pernafasan menggunakan peranti pemantau kualiti udara. Penemuan mendedahkan bahawa sumber bahaya berubah bergantung pada tujuan stesen kerja. Akhir sekali, dua pengubahsuaian dicadangkan pada susun atur asal kilang untuk mengurangkan zarah habuk di dalam kilang: (1) Pengubahsuaian pada saiz salur masuk dan salur keluar utama; (2) Pengubahsuaian pada lokasi salur masuk dan salur keluar utama. Tiga situasi telah disimulasikan untuk setiap kategori pengubahsuaian untuk meramalkan corak aliran udara di kilang yang disiasat. Keputusan mencadangkan bahawa kedua-dua salur masuk dan salur keluar perlu mempunyai saiz yang sama untuk aliran udara yang lancar dan lokasi salur keluar perlu ditukarkan ke tengah hujung kilang untuk mengurangkan kawasan halaju sifar. Penambahan salur masuk di salah satu stesen di dalam kilang juga dicadangkan untuk keputusan yang lebih baik.

Kata Kunci: Debu kayu, Aliran udara, Pengiraan dinamik bendalir, Bahan zarah, Industri perabot.

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LIST OF SYMBOLS AND ABBREVIATIONS

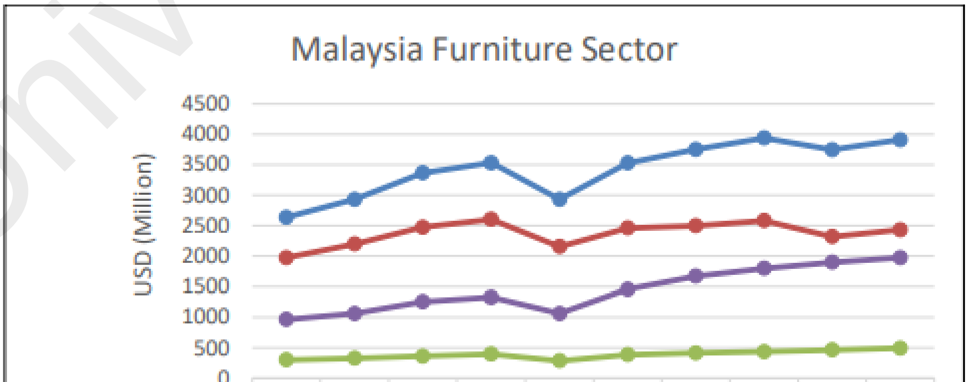
AQI	:	Air quality index
CNC	:	Computer numerical control
CFD	:	Computational fluid dynamic
DOSH	:	Department of Occupational Safety and Health
FMA	:	Factories and Machinery Act
OSHA	:	Occupational Safety and Health Act
OEL	:	Occupational exposure limits
PM	:	Particulate matter
PPE	:	Personal protective equipment
PEL	:	Permissible exposure limit
NIOSH	:	National Institute for Occupational Safety and Health
WHO	:	World Health Organization
SOCSO	:	Malaysian Social Security Organization
IV	:	Industrial Ventilation
TLV	:	Threshold limit value

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Malaysian Furniture Industry

Malaysia's development in the furniture industry over the previous three decades has been impressive, growing from a small cottage sector to a multibillion-dollar export-oriented industry. Malaysia was identified as one of the fastest-growing countries manufacturing furniture in the wood-based industry sub-sector. Malaysia was currently competing with China and Vietnam in the production of low-cost wood-based furniture. Malaysia's main destinations are the United States, Japan, and Australia, and it was ranked the 9th largest furniture exporter in the world in 2017 with an export value of over 2.1 billion USD. In the years 2013 and 2014, the United States of America received about 30% of Malaysian furniture exports, worth RM 2.1 billion and RM 2.3 billion respectively. In 2013, global furniture production was expected to be worth USD 456 billion, with a market share of 10% to 15% growing year after year. According to the Ratnasingam and others, Malaysian furniture sector is considered matured industry because it has shown friendly and constructive development despite facing various obstacles and challenges (Ratnasingam et al., 2018).



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Production	2636	2931	3365	3531	2930	3529	3751	3940	3747	3911
Exports	1973	2198	2474	2602	2155	2459	2496	2580	2317	2432
Imports	303	330	363	397	288	388	416	437	467	494
Consumption	965	1062	1254	1326	1063	1458	1671	1797	1897	1973

Figure 1.1: The Progress of Malaysian Furniture Sector since 2005. (CSIL, 2015)

1.2 Manufacturing Industry Dust

Manufacturing is the process of turning raw materials into finished things using labour, machinery, tools, and biological or chemical processing or formulation. Manufacturing can refer to the large-scale transformation of raw materials into completed goods or the creation of more complicated items by supplying basic goods to manufacturers for the construction of automobiles, aero planes, and household appliances. Due to its unique nature, Malaysia's manufacturing industry is one of the most hazardous. The machining process is critical for high-quality products since it is a value-added operation in furniture manufacturing.

During the manufacturing or production process, industrial dust, also known as process dust, is produced mainly during cutting, drilling, grinding, and sawing operations. Dust is produced by manufacturing, residential, and industrial activities. According to BS6069, dust refers to all particulate matter with a diameter of up to 75 μm and includes both suspended and deposited dust (British Standards Institution, 1988). Excessive dust emissions generate a variety of health and industrial issues, including health risks, the possibility of dust explosions and fire, equipment damage, reduced vision, unpleasant odours, and even community relations issues. Excessive or long-term exposure to harmful respirable dust may result in a respiratory disease. Factory workers are required to have some basic safety awareness to be sensitive to potential hazards in their workplace. Factory manufacturing procedures frequently generate a huge number of particles. These particles frequently reach the air in occupied areas, posing a major threat to workers' health (Hsu et al., 2012).

1.3 Problem Statement

Dust particles generated from the manufacturing industry can be so small that they are invisible to the naked eye. The smaller size of dust particles makes it difficult to be manage as it will escape to the air to become airborne dust. At higher level of exposure, those particles can be hazardous since they inhable into the lungs and can induce adverse health effect. The influence of better ventilation system also plays a crucial role since it is a necessary system in any manufacturing industry to provide a healthy and safe working environment for workers as well control over contaminant or dust released in an indoor work environment. Nonetheless, the severity of risky exposure to the dust particle, its implications, and the solution are not yet well defined.

1.4 Research Objectives

Several objectives have been developed for this study based on the problem statement. The objectives are:

1) To investigate the generation of dust particles as a by-product in manufacturing.
2) To simulate the transmission, emersion and dispersion of dust particles from the generation site.
3) To propose solutions in containing the dust particles from becoming a serious hazard in the industry.

1.5 Scope of Research

The scope of this research will be defined according to the objectives stated. Industrial dust, also known as process dust, is generated during the manufacturing or production process. Cutting, drilling, grinding, or sawing are examples of manufacturing process that generates dust. Dust particles are often an unwanted by-product of machining materials. Managing dust particles are challenging due to its size. Despite isolating the work area, dust particles would always escape. There are a lot of research that had been carried out regarding the effect of dust particle towards human health however there are less studied about the simulation of dust particle in the manufacturing industry. Therefore, simulating and learning the flow of dust particles would make it easier to control it. The solution to eliminate, monitor and reduce the formation of dust particle form becoming a serious hazard also are proposed in this study.

CHAPTER 2: LITERATURE REVIEW

2.1 Dust: Definition and Concept

Airborne pollutants come in two forms: gaseous (gases and vapours) and aerosolized (aerosols). In scientific terms, an aerosol is a collection of particles suspended in a gaseous medium, most commonly air in the context of occupational hygiene. Aerosols can be found in the form of dusts, sprays, mists, smokes, and fumes in the air. All of these kinds may be essential in the workplace because they are linked to a wide spectrum of occupational disorders. Airborne dusts are of significant concern because they have long been linked to traditional occupational lung disorders like pneumoconiosis, as well as systemic intoxications like lead poisoning, particularly at higher levels of exposure (Johnston, 2000).

The size of dust particles ranges from visible to invisible. The smaller the particle, the longer it can remain in the air and travel further. Large dust particles fall out of the air near to the point of origin. These particles are responsible for the dust layers that may be seen on items such as furniture and automobiles. As human breathe in large dust particles, they tend to become stuck in human's nose and mouth, but they can be easily exhaled or ingested safely. Ultrafine dust particles can be absorbed straight into the bloodstream, but very minute dust particles are more likely to enter deeper into the lungs.

2.1.1 Classification of Dust

According to the World Health Organisation (WHO), "Dusts are solid particles, ranging in size from below 1 μm up to at least 100 μm, which may be or become airborne, depending on the origin, physical characteristics and ambient conditions." Manual procedures such as cutting, crushing, and grinding can generate dust, and the particles can be so minute that they are invisible to the naked eye. Varied types of dust provide different health hazards, and they can be divided into three categories L Class (Low Risk), M Class

(Medium Risk) and H Class (High Risk). Every class has a maximum allowed concentration as displays in the Table 2.1, which every employer must be aware of.

Table 2.1: Classification of dust in industry (Girts, 2020)

Class of Dust	**Description**	**Max Allowable Concentration (MAC)**
L class Dust (Low risk)	Lower toxicity and includes simple house dust, soil, general construction dust/waste, soft woods and solid surface material.	Less than 1 mg/m^3
M Class Dust (Medium Risk)	Include hard woods, board material, man-made woods (MDF), filler and clear coats, cement, tile cement, brick, mortars (silica), concrete dust, quartziferous materials (e.g. sand) and paints, such as oil paints and latex.	Max of 1 mg/m^3
H Class Dust (High risk)	High toxicity dusts containing pathogenic or carcinogenic particles, as well as asbestos, mould spores, bitumen, mineral fibres and artificial mineral fibres, like glass wool.	Less than 0.1 mg/m^3
Combustible dust	Combustible substance, mixed with air and with the addition of a source of ignition will cause an explosion.	NA

2.2 Particulate Matter

Airborne particulate matter (PM) is a mixture of several chemical species floating in the air, instead of just a single pollutant. PM comes in different sizes and shapes and can also be made of hundreds of different chemicals (US EPA, 2016). Small droplets of liquid, dry solid fragments, and solid cores with liquid coatings make up this complicated mixture of solids and aerosols. Inorganic ions, metallic compounds, elemental carbon, organic compounds, and chemicals from the earth's crust can all be discovered in the particles, which vary in size, shape, and chemical composition. For the purposes of air quality regulation, particles are classified according to their diameter. Those with a diameter of 10 microns or less (PM10) are inhalable into the lungs and causing health problems. While particle with a diameter of 2.5 microns or less (PM2.5) are classified as fine particulate matter. Therefore, PM2.5 comprises a portion of PM10. The comparison in the particulate size between both PM is shown in Figure 2.1.

2.2.1 PM2.5 and PM10

Small particles with an aerodynamic diameter of less than 2.5 micrometers (known as PM2.5) are the most hazardous since they can penetrate deep into the lungs and even enter the bloodstream. Particles can arise from foundries and diesel engines, for example. If the concentration is high enough, those with an aerodynamic diameter of less than 10 micrometers (known as PM10) can cause major health impacts in vulnerable persons. PM10 and PM2.5 are generally derived from various sources, and their chemical compositions are likewise varied. In the table below, the relative diameters of PM10 and PM2.5 particles are compared. Table 2.2 summarizes the general features that separate fine (PM2.5) and coarse (PM10) mode particles.

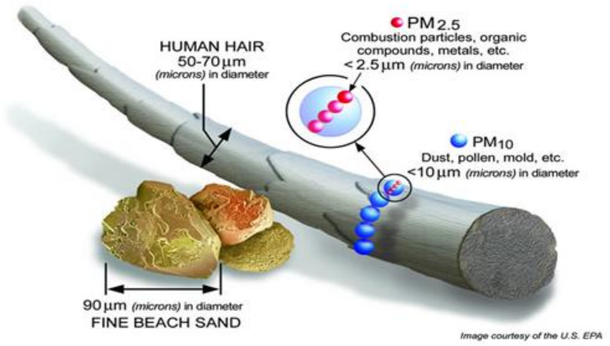


Figure 2.1: Comparison of particulate size

Table 2.2: Comparison in the characteristic of PM2.5 and PM10

Characteristic	Fine mode particles ($PM_{2.3}$)	Coarse mode particles (PM_{10})
Diameter	Less than 2.5 µm	Less than 10 µm
Composed of	Sulfate, SO_2^{4-}; nitrate, NO^{3-} ; ammonium, NH^{4+} ; hydrogen ion, H^+; elemental carbon, C; organic compounds; PAH; metals, Pb, Cd, V, Ni, Cu, Zn; particle-bound water; and biogenic organics.	Resuspended dust, soil dust, street dust; coal and oil fly ash; metal oxides of Si, Al, Mg, Ti, Fe, $CaCO_3$, NaCl, sea salt; pollen, mold spores, and plant parts.
Sources	Combustion of coal, oil, gasoline; transformation products of NOx, SO_2, and organics including biogenic organics, e.g., terpenes; high temperature processes; smelters, and steel mills.	Resuspension of soil tracked onto roads and streets; Suspension from disturbed soils, e.g., farming, mining; resuspension of industrial dusts; construction, coal and oil combustion, and ocean spray.
Lifetimes	Days to weeks	Minutes to hours
Travel distance (km)	100 to 1000	1 to 10
References	Cheung et al., 2011	R. W. Atkinson et al., 2010

2.3 Source of Dust Particle

Dust particles in the environment which known as particulate matter (PM) as had been mentioned previously can come from a multitude of sources. The size and chemical makeup of the particles vary greatly depending on the source and the particles' history. Particulate matter can be produced mechanically, such as by the wind, discharged directly into the atmosphere, or synthesized in the atmosphere via interactions between precursor gases.

Table 2.3: Sources of dust particle (Thorpe et al., 2008; Witham et al., 2009)

Major source of Dust particle	Chemical reaction of gases in atmosphere	Combustion process	Mechanical generation
Description	production of small particles of a few nm diameters which grow relatively quickly by coagulation	include industrial and transport related combustion processes, which directly emit fine particles, typically in the size range 0.1 - 2.5 µm diameter	produces coarse particles (2.5 - 20 µm) which are distributed by wind turbulence
Sources	- sulphates that formed from the atmospheric reaction of sulphur dioxide (SO_2) derived from man-made -natural emissions of non-methane volatile organic compounds (NMVOCs), in the presence of sunlight	-carbon containing particles (soot) emitted from the combustion of carbon-based fuels (coal, oil, natural gas) by industry and vehicles -fly-ash particles that emitted from high temperature combustion of coal	. -mineral-containing particles are emitted from erosion of agricultural soils, volcanic eruptions, quarrying and building activities -cement and fertilizer dusts come from factories and construction sites

2.4 Transmission of Dust Particle in Air

2.4.1 Brownian Motion

The random motion of particles suspended in a medium is known as Brownian motion or it also can be called as pedesis. Brownian motion enables the particles to move in a zig-zag pattern, resulting in a partial or total transfer of energy between them. The particle size is inversely proportional to the speed of motion. This means that smaller particles move faster than larger particles. Furthermore, because momentum transfer is inversely proportional to particle mass, smaller particles obtain more energy and move faster after colliding.

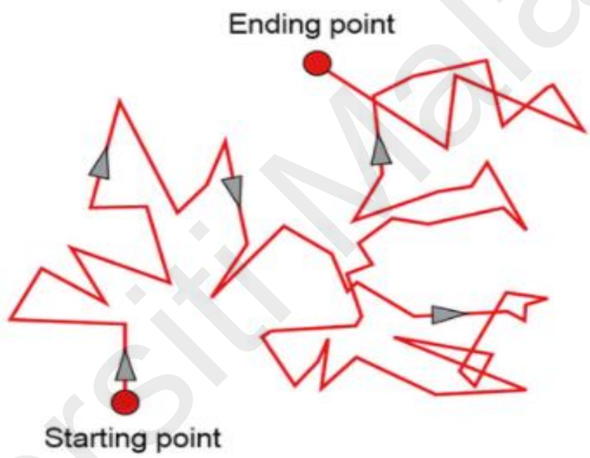


Figure 2.2: Random movement of dust in air

Dust particle in air form a colloid. The zig-zag motion of microscopic dust particles suspended in air is caused by collisions with fast-moving air particles. As shown in the Figure 2.2, Brownian motion is the random movement of particles. The air molecules are constantly moving and colliding with the dust particles. Because the molecules are travelling in a variety of directions, they clash with dust particles from different directions. The darting motion of the dust is caused by this activity, as atoms and molecules are constantly in motion.

The movement of airborne particles in the atmosphere creates a dust cycle, which includes emission, transport, and deposition activities. The transmission of particles from the atmosphere to any ground surface is known as dust deposition. Factors such as the properties of airborne particles, atmospheric flow conditions, and the underlying surface features all influence this process. The particles are collected by the surface due to impaction, interception and Brownian motion. They are either retained to or rebounded from the surface, depending on a combination of surface and particle properties (Beckett et al., 1998).

2.4.2 CFD Simulation of Dust Particle – Previous Research

Model airflow characteristics that are hard to evaluate using experiments can be predicted and analysed using numerical analyses based on computational fluid dynamics (CFD) (Yun, 2002). Many numerical simulations of dust dispersion characteristics have been undertaken in recent years in order to solve occupational health problems. Nevertheless, the simulation of airflow within the wood furniture industry have not been done yet. Many studies in the wood sector have focused solely on the impact of machining parameters such as speed, angle of rotation, and others. Hence, the focus of this research is on the simulation of airflow within furniture industry. Table 2.4 summarises the findings of previous studies that used the commercial simulation software Ansys to simulate airflow and dust distribution in several applications and research areas.

Table 2.4: Summary on CFD Simulation analysis of air flow and dust particle based on previous research

Year	Author	Description	Modelling tool
2005	Balusu et al., 2005	Modeled the ventilation and respirable dust flow characteristics around a shearer and evaluated the effects of different dust control measures	Computational Fluid Dynamics (CFD)
2010	Toraño et al., 2011	Combined field tests and numerical simulations to study the migration behavior of dust in air	Computational Fluid Dynamics (CFD)
2018	Yu et al., 2018	Simulated air velocity distribution and air flow duct to predict the airborne dust distribution based on a model of college students' dormitory and compare with result from the dust sensor	Computational Fluid Dynamics (CFD)
2019	Bahloul et al., 2019	Modeled and measured dispersion and distribution of ultra-fine particles (UFP) in a granite polishing process	Computational Fluid Dynamics (CFD)
2020	Fatimazzahra & Bachir, 2020	series of simulations are carried out to investigate dust dispersion behavior by carried out study regarding the positions of the air inlet and to full airflow of dust	Computational Fluid Dynamics (CFD)
2020	Qian et al., 2020	Obtain a fundamental understanding of the airflow patterns and the fine dust dispersion characteristics during a polishing process	Computational Fluid Dynamics (CFD) coupled with-Discrete Phase Model (DPM),
2021	Wu et al., 2021	Explore microscopic migration and macroscopic diffusion of dust particles in the mining area by numerical simulation method	Fluent 13.0 numerical simulation software

2.5 Dust as Health and Occupational Hazard

The finest particle visible to the naked eye while suspended in air is around 50 to 100 mm in diameter, but as previously stated, it is the particles with a diameter of 0.2 to 5 mm that are the most hazardous to the lungs. As a result, the presence of visible dust is just a poor indicator of risk, as finer, unseen particles are probably certainly present as well. The absence of visible dust is no guarantee that harmful dust is not present in the air. The large visible particles in a dust cloud will immediately fall to the ground, but the fine deadly particles will require several hours to reach the ground. Airborne dusts found in industrial applications are typically less than 10 mm in size and can be ingested, absorbed via the skin, or inhaled into the body. Although the former is rarely a significant issue, skin illnesses do develop on a regular basis. Inhalation, on the other hand, is the most severe threat for workers in a dusty workplace. (Manisalidis et al., 2020).

Table 2.5 below shows presents the number of instances of occupational diseases reported to the Malaysian Social Security Organization (SOCSO) by causal agent and target organ system for the years 2007, 2008, and 2009. The main source of concern would be workers' bad health as a result of a lack of awareness of the disease-causing substance in their workplace and its target organ in human respiratory systems.

Table 2.5: Selected occupational disease by causal agent and target organ respiratory system by SOCSO for the year 2007,2008 and 2009(Paiman et al., 2013)

Occupational disease by causal agent	**No of cases reported**		
	2007	2008	2009
Dusts	167	107	56
Gases, vapors, fumes	34	36	34
Liquids not elsewhere classified	133	118	74
Chemicals not elsewhere classified	94	57	56
Others - dusts, gases, liquids, chemicals	189	91	87
Occupational Disease by Target Organ Respiratory System	**No of cases reported**		
	2007	2008	2009
Pneumoconioses caused by sclerogenic mineral	5	7	5
Bronchopulmonary diseases caused by hard metal	1	3	2
Bronchopulmonary diseases caused by cotton	0	1	1
Occupational asthma caused by sensitizing agents or irritant inherent to the work process	4	10	10
Extrinsic allergic alveolitis	0	2	2
Chronic obstructive pulmonary diseases	2	3	4
Diseases of lung, due to aluminium	0	2	17
Upper airways disorders	3	0	1
Any other respiratory diseases	9	21	11

2.5.1 Dust Exposure Standard and Regulation

The World Health Organization (WHO) has a set of standards for monitoring and lowering PM exposure, which include PM10 and PM2.5 for 24-hour/annual averages of 50 g/m^3, 25 g/m^3 and 20 g/m^3, 10 g/m^3, respectively. This guideline serves as a benchmark for countries to use when establishing air quality guidelines. Table 2.6 shows the average PM exposure standards established by different nations based on WHO guidelines.

Table 2.6: PM average exposure standards of selected countries

Countries	TSP 24-hr (μg/m³)	TSP Annual (μg/m³)	PM_{10} 24-hr (μg/m³)	PM_{10} Annual (μg/m³)	$PM_{2.5}$ 24-hr (μg/m³)	$PM_{2.5}$ Annual (μg/m³)
Australia			50		25	8
WHO			50	20	25	10
EU			50	40		25
South Korea			100	50	35	15
US			150	50	35	15
Japan			200	100	35	15
Vietnam	200	140	150	50	50	
India			100	60	60	40
Pakistan	500	360	150	120	35	15
China	300	200	150	70	75	35
Nepal		230	120		50	
UAE	230	90	150			

Australia has the highest standards compared to the WHO guideline, with PM2.5 24-h exposure at 8 μg/m3 and 25 μg/m³ for PM2.5 annual exposure (Ministry of Environment, Australian Government, 2005). In South Korea, it has pointed out that the environmental standards for PM2.5 are significantly eased compared to the WHO, the US and Japan, and the International Agency for Research on Cancer (IARC) appointed PM as a group 1 carcinogen, which led the environmental standard of PM2.5 strengthened to 35 μg/m³ daily average and 15 μg/m³ annually, respectively (Department of Environment South Korea, 2018). Many other countries have lower standards than the WHO guidelines. After analyzing the standards of different countries, it was concluded that developed countries had established standards closer to the WHO guidelines and developing countries have much lower standards than the WHO guidelines.

In Malaysia, occupational exposures are governed by the Factories and Machinery Act (FMA) of 1967, as well as the more comprehensive Occupational Safety and Health Act (OSHA) of 1994. The attitude of occupational safety and health legislation shifted with OSHA 1994, from one that was very prescriptive and contained extensive technical provisions under FMA, 1967, to one that is more efficient and fosters self-regulation. The expenditures of transforming Malaysia into a developed country by 2020 should be borne by the Malaysian worker. Rapid industrialization has brought not only cutting-edge technology but also plenty of new hazards to the country's workplace.

To address these risks, the government has established multiple regulations and established occupational exposure limits (OEL) for these workplace hazards with the support of the National Institute for Occupational Safety and Health (NIOSH), employer federations and trade unions, universities, and safety and health professionals.

The permissible exposure limit (PEL) by OSHA for airborne total dust not to exceed 15 mg per cubic meter (mg/m^3) over an 8-hour TWA limit for workplace exposures to total dust. Total dust refers to a wide range of particle sizes, some of which are too large to reach the deepest parts of the lungs but can still enter the nose, mouth, and upper airways during breathing. Meanwhile, for workplace exposures to respirable dust, OSHA sets a PEL of not more than 5.0 mg/m3 over an 8-hour TWA limit.

2.6 Manufacturing Industry as Hazardous Industry

The great majority of workers in the furniture manufacturing industry are exposed to hazardous working conditions that are filthy, unhealthy, and degenerative. Previous research has found a direct link between the prevailing work environment and industrial accidents (Carrillo-Castrillo et al., 2013). Dusty environments and excessive chemical exposure are two of the most important causal variables. In the furniture manufacturing sector, machining techniques, particularly routing and sanding, produce considerable quantities of dust emissions.

The working area airflow region, employees' rate of inhalation, and the ventilation system all influence dust exposure levels in the workplace, while the toxicity level is governed by the type of material used and the size of the dust particles created (Ratnasingam et al., 2010). Factory manufacturing processes frequently generate a huge number of particles. These particles frequently enter the air in occupied areas, posing a major threat to employees' health (Hsu et al., 2012).

2.6.1 Wood Dust Exposure

Wood dust is one of the most common organic dusts that workers in the wood furniture manufacturing industry are exposed to. Wood dust exposure has been linked to health problems such as nasal mucosa damage, inflammation, and sinus cancer, while deep lung deposition has been related to lung cancer and impaired respiratory function (Siew et al., 2012). Wood dust emissions are particularly high during wood machining procedures such as shaping, routing, and sanding. Nonetheless, the working area airflow field, the worker breathe-in rate, and the air capture system influence wood dust exposure levels, while the extent of its harmful effects is determined by wood dust attributes such as wood species and particle size (Ratnasingam et al., 2010).

Sanding is a cutting method that is orthogonal and has a negative rake angle. It signifies that the cells' pressing and scraping actions remove the wood. This process finally results in the production of wood dust, which is hazardous to workers' health. Considering the industrial consequences, there are limited studies on dust emission during the sanding procedures of Malaysian hardwoods (Ratnasingam et al., 2011). Dust emission characteristics during machining processes are a crucial raw material criterion that influences the optimal utilisation of dust during product manufacturing. Dust emissions have a significant impact on workers' health and, as a result, indirectly reduce factory efficiency.

Machining and abrasive sanding are key sources of dust emission in the manufacturing process, with the latter having a more noticeable dust emission effect than the former. The workpiece density and hardness, abrasive sanding grit, kind of abrasive material, and machining parameters all influence the amount of dust produced (Ratnasingam et al., 2019).

2.6.2 Effect of Wood Dust

When machines or tools are used to process wood, wood dust is formed as a by-product of the operation and is not produced for any specific purpose (Mohan et al., 2013). The most common occupational exposure hazard in the wood industry is airborne wood dust (Siew et al., 2012). According to Mandryk in his research, wood dust is an accumulation of any wood particulate that is generated during the processing or handling of wood. As this dust becomes airborne it may be inhaled by workers, leading to mucosal irritation, allergies and respiratory system cancer (Pellegrini 2002). Humans have been linked to upper and lower respiratory symptoms such as cough, wheezing, sputum production, and shortness of breath after inhaling wood dust (Ea & Tf, 2015).

Exposure to wood dust is a common occurrence among working-age populations. Wood dust is one of the most significant occupational exposures, according to the International Agency for Research on Cancer (IARC), with millions of workers globally vulnerable. Wood dust is created in a range of wood activities, including grinding, sanding, cutting, milling, and debarking (Labrèche et al., 2013).

Construction employees in the furniture industry are frequently exposed. In the wood furniture industry, the machining procedures release wood dust into the air. The health effects of wood dust are thought to be dependent on the wood species utilised, with non-malignant effects being associated with pine, oak, beech, and red cedar (Sripaiboonkij et al., 2009).

In general, wood dust exposure has been linked to a high prevalence of respiratory symptoms and disorders, such as mucous membrane and nasal airway irritations, chronic and acute impairment of lung function, asthma, and allergies (Douwes et al. 2010; Estlander et al., 2001). Aside from that, another symptom that was identified in several research was breathe shortness. This symptom was typically linked to a high rate of chest tightness and wheezing. (Krawczyk-Szulc et al., 2014). Finally, there were other health symptoms such as irritations of the mucous membranes and the nasopharyngeal cavity.

2.7 Industrial Ventilation: Definition and Concept

Industrial ventilation accounts for many different definitions. From the perspective of an environmental engineer, IV (Industrial Ventilation) means the design and application of equipment to provide the necessary conditions for maintaining workers' efficiency, health, and safety while from the perspective of an industrial hygienist, it means the control of emissions and exposures to hazardous environments. Finally, from the perspective of a mechanical engineer, it implies environmental control via air flows, as well as the replacement of contaminated air with clean fresh air (Iglesias Estellés, 2018). Ventilation, in general, moves outdoor air into a building or a room and distributes the air within the building or room. The basic goal of ventilation in buildings is to produce healthy air for breathing by diluting and eliminating contaminants that originate in the structure (Awbi, 2003).

According to Murga et al, ventilation is one of the most significant factors in improving factory thermal conditions and potentially reducing pollutants (Murga et al., 2020). Effective ventilation systems can lower airborne particle concentrations to tolerable levels while simultaneously maintaining a comfortable indoor temperature (Caputo & Pelagagge, 2009). As a result, it plays an important role in enhancing the overall quality of the industrial environment and helps to prevent numerous harms to people and machines. Despite the fact that there are multiple types of mechanical ventilation systems that differ in terms of air distribution, mechanical ventilation strategies are the most widely employed systems in industries. One of the most significant factors in attaining good ventilation is identifying the proper approach for the type of industry and climate. There are three main types of industrial ventilation: natural, diluting and exhaust.

2.7.1 Natural Ventilation

Natural ventilation is among the most widely used sustainable options for sustaining healthy and thermally comfortable inside environments while consuming less energy than other ventilation strategies (Ji et al., 2009). For some commercial buildings, natural ventilation offers the potential to save initial and running costs while maintaining ventilation rates that are consistent with acceptable indoor air quality (Emmerich et al., 2001). Natural factors such as winds and thermal buoyancy force caused by a difference in internal and outdoor air density propel outdoor air through purpose-built building envelope openings.

Windows, doors, solar chimneys, wind towers, and trickling ventilators are examples of purpose-built openings. Natural ventilation, on the other hand, isn't exactly a mechanical system. They are openings which can be constructed in the ceiling, sides, and floor to allow the ambient air to circulate. Climate, building design, and human behavior all influence natural ventilation in buildings (J. Atkinson et al., 2009) The major goal is to remove the hot and hazardous air produced by the machinery and to enable clean air to enter the space. However, concerns about the system may arise, such as the reliability of outdoor air ventilation rates, the distribution of this outdoor air within the building, moisture control in naturally ventilated buildings, building pressurization issues, and the entry of polluted air from the outside without the option to filter or clean it.

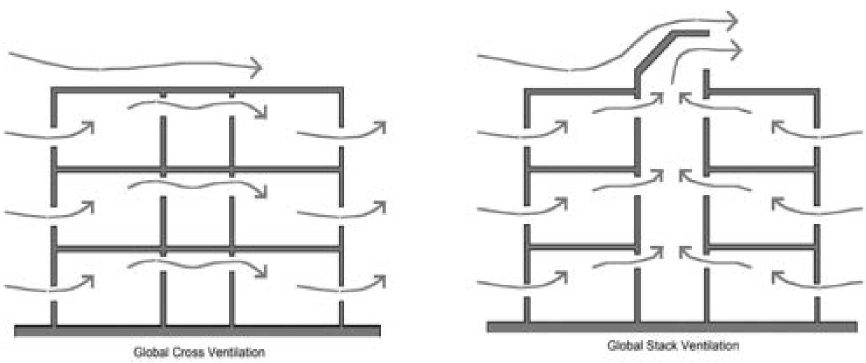


Figure 2.3: Example of natural ventilation

2.7.2 Diluting General Ventilation

The system supplies and exhausts a huge amount of air to and from an area or building in this sort of ventilation. Large exhaust fans are frequently installed in the building's wall or roof. By ventilating the entire workplace, dilution ventilation reduces pollutant emissions at a worksite (Government of Canada, 2022) General ventilation disperses contaminant to some extent across the entire worksite, potentially affecting those who are far away from the source of contamination. When the exhaust fan is closed to expose workers and the makeup air is positioned behind them, the contaminated air is pulled away from the workers' breathing zone, therefore dilution ventilation becomes more efficient. The purpose of dilution ventilation system is to dilute the concentration of contaminants in the air with uncontaminated air so as to reduce the concentration below a given level, usually the threshold limit value (TLV) of the contaminant (Talty, 1998).

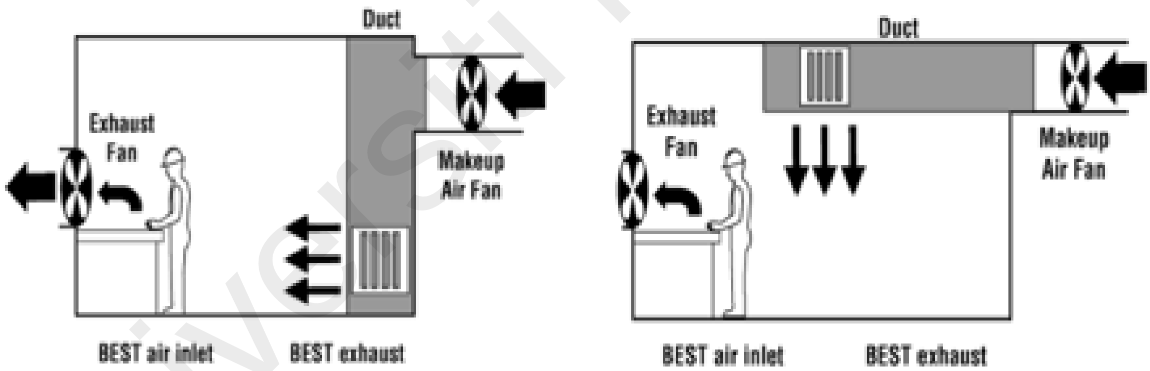


Figure 2.4: Example of general ventilation

It is performed by withdrawing or adding air to cause the air in the workplace to move, allowing the polluted air to mix with the incoming uncontaminated air. It is vital to have air movement for a dilution ventilation system to achieve its goal. The pollutant will travel slowly within the workroom atmosphere if the air is stagnant. Thus, the highest concentration will be present near the source and, as a result, in the worker's breathing zone.

2.7.3 Local Exhaust Ventilation

Exhaust ventilation systems work by depressurizing the building and lowering the inside air pressure below that of the outside air. The stale air is drawn out of the building via an exhaust mechanism and a ducting system on the exterior. Fresh air is then introduced from a separate source, usually another air vent.(Russell et al., 2007). Exhaust ventilation is the most effective approach for preventing contaminants, as the primary purpose is to prohibit polluted air from entering the workplace, preventing workers from inhaling these compounds. According to Meng et al, a typical exhaust ventilation system consists of fans attached to a centrally situated exhaust point and is relatively simple and affordable to construct (Meng et al., 2019).

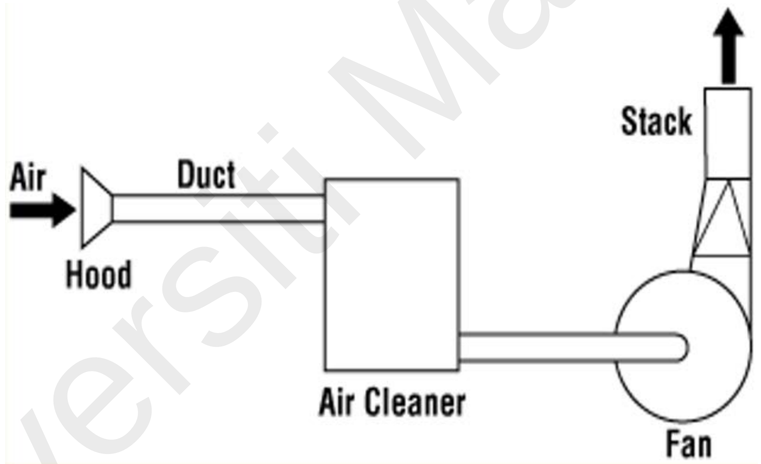


Figure 2.5: Local exhaust system

Based on the Figure 2.5 above, it show that local exhaust system has six basic element including: i) hood that captures contaminant at the source; ii) Ducts that transport airborne particle through system; iii) air cleaner that removes the contaminant from the moving air; iv) fans that move air through the system and discharge the exhaust air to outdoor; v) exhaust stack through which the contaminated air is discharged; vi) make up air that replaces the exhausted air.

2.8 Dust Control Approach

Following the quantification of the worker's exposure to airborne dust, standard dust control measures can be used to keep the dust concentrations in the region under control. In effort to protect workers from excessive dust exposures, certain industrial processes, such as those used in the manufacture of industrial minerals, may employ same control mechanisms like engineering controls, work practices, and the use of personal protective equipment.

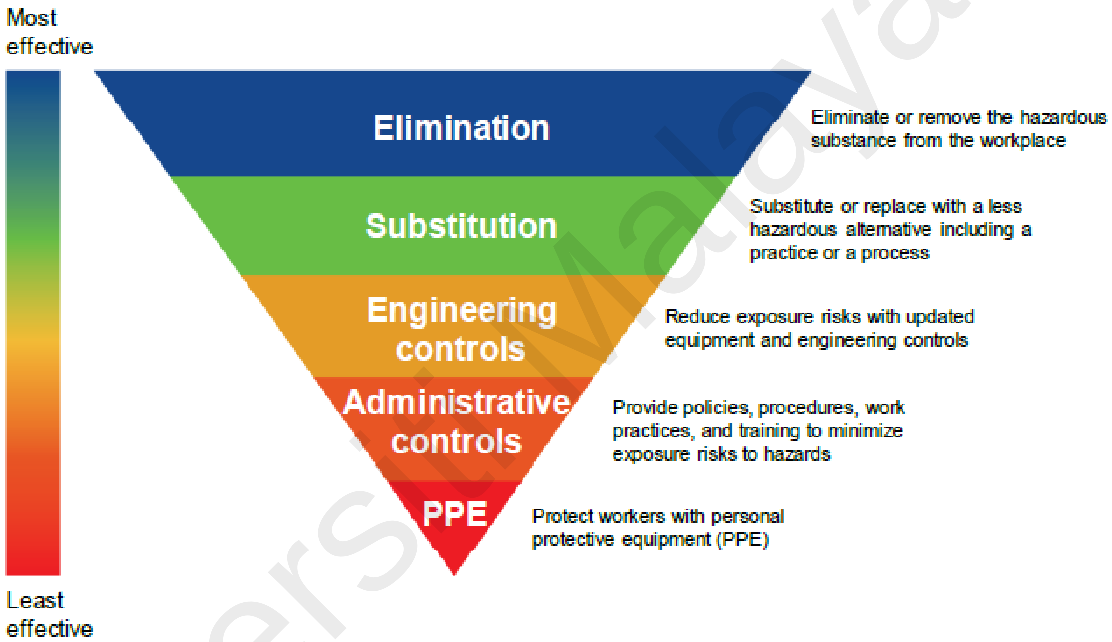


Figure 2.6: Illustration of the hierarchy of controls approach (adapted from NIOSH 2018a)

By referring to the figure above, the most effective approach of addressing the hazard is at the peak of the inverted pyramid. As one proceeds down the inverted pyramid, the predicted level of efficiency associated with that type of control declines. One of the best ways to avoid worker overexposure is to remove the hazard entirely from the operation or replace it with a material that poses a lower risk.

2.8.1 Elimination and Substitution

The term "elimination and substitution" refers to the removal of a hazard from the workplace or the replacement of hazardous materials or machines with less harmful alternatives. The only true proactive control for removing exposure sources prior they reach the workplace is elimination. As a result, eliminating the hazard—by designing it out—should typically be the first alternative explored. Elimination, on the other hand, is the hardest to implement. If dust cannot be completely eradicated from the workplace, a less harmful material can be utilized to provide better protection.

2.8.2 Engineering Control

Plants, equipment, ventilation systems, and operations that are designed or modified to limit the origin of exposure are referred to as engineering control. Engineering controls are divided into a few categories. Process control is the first. To reduce risk, process control entails modifying the way a work activity or process is carried out. Evaluation should be done both before and after the modification is made to ensure that the adjustments were successful in controlling the hazard. When drilling or grinding, for example, utilise wet rather than dry processes. The "wet approach" is spraying water on a dusty surface to reduce dust levels or mixing material with water to avoid dust formation.

Next is ventilation. Ventilation is a means of controlling air in the workplace by carefully "adding" and "removing" it. If appropriately designed, ventilation can remove or dilute an air pollution. Almost all chemicals and procedures can benefit from local exhaust ventilation. It eliminates the contamination at the source, preventing it from spreading into the work environment, and it uses lower exhaust rates than standard ventilation.

As engineering controls are developed to minimize the hazard at the source or sources before the worker encounters the hazard, therefore they are preferable over administrative and PPE controls. When elimination and substitution are not possible, these kinds of controls should be used and viewed as the first line of defense. They give the maximum level of safety for the worker. One of the reasons they are so effective is that, while they do require maintenance, they frequently operate independently of worker decisions and actions. Although the upfront costs of developing and integrating engineering controls may be greater, operational and process expenses may be reduced over time.

2.8.3 Administrative Control

Administrative controls are frequently used as a supplement to current engineering controls, during the installation and testing of engineering controls, or in situations where hazards are difficult to manage but relying on engineering controls as the main technique of worker protection is impossible. Workers' exposures are limited by administrative controls such as scheduling shorter work durations in contaminated regions or enforcing other "rules." Because the hazard is not actually removed or lessened, these control strategies have significant limitations. Administrative controls are not widely used because they are complex to set up and maintain, and they are not a dependable technique to reduce risk. Proper work practices, cleaning, maintenance, and personal hygiene are common examples administrative controls that depend on worker engagement to limit dust exposures. Hazard awareness training, job rotation, and written job procedures also fall within administrative controls.

2.8.4 Personal Protective Equipment (PPE)

Respirators, protective clothing including gloves, face shields, eye protection, and boots are instances of personal protective equipment (PPE) that act as a boundary between the wearer and the chemical or material. PPE, particularly respirators, should only be used as a last option if the control of inhalation hazards cannot be achieved using the methods recommended in the hierarchy of controls outlined above, and they should not be considered a substitute for other controls. Despite engineering controls are the recommended approach of mitigating workplace dangers, personal protective equipment (PPE) is required in many circumstances.

First and foremost, when engineering controls are not practicable, personal protective equipment (PPE) plays an essential role, particularly for employees, in providing additional protection for infrequent entrance into hazardous environments to conduct investigations or maintenance. However, dependence on personal protective equipment (PPE) has some drawbacks. Workers who use respirators, for example, must participate in a respiratory protection programme that includes training, annual fit testing, and medical exams to determine their eligibility to wear respirators. Next, to prevent mask degradation and guarantee that their protective capacity is not compromised during usage, respirators must be inspected before and after each use, as well as correctly stored, which may be inconvenient for employees. Finally, while personal protective equipment (PPE) is initially affordable, it is costly to keep over time. Administration of such a program can be very costly.

CHAPTER 3: METHODOLOGY

3.1 Project Flowchart

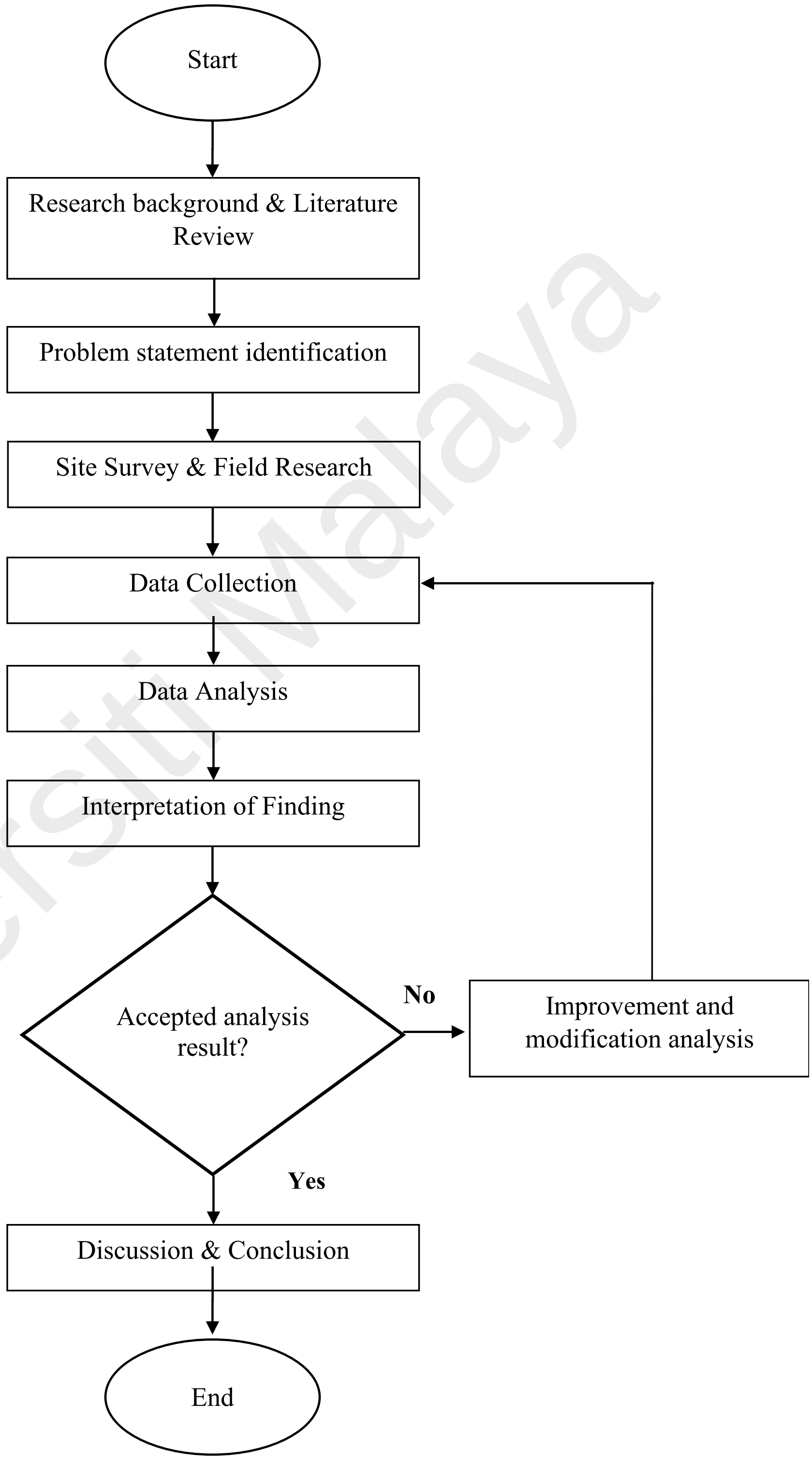


Figure 3.1: Overall Project Flowchart

For first stage is Research Background and Literature Review study which focuses primarily on the compilation of information regarding the title including type of dust particle, motion of dust particle in air, their effect towards the health and the ventilation system used in manufacturing nowadays. Appropriate data and information will ensure that the study can be performed according to schedule successfully. Then from the findings and existing research gain, the problem and the current issues occur in the manufacturing industry will be identified.

Next are Site Survey and Field Research where at this stage, one manufacturing factory was chosen as the investigated factories throughout this research to study the layout of the factory, the airflow within the factory and to find out the existing ventilation system as well as the dust control measure used to control the dust particle inside the factory.

The simulation of the air flow within the factory are done to identify the movement of the dust as it being generated during production hours. Firstly, the 2-Dimensional factory layout are being sketched. By considering the Malaysia's mean annual wind speed which is 2 m/s and the fan used within the factory therefore we assuming the velocity of the air travel across the factory to be 5 m/s in total. By setting the velocity of the air at the inlet of the factory with 5m/s, then we run the analyses and identify the finding where the result will be discussed later in Chapter 4.

Next, for the validation purposes for the simulation done on the air flow inside the factory, concentration amount for particulate matter are collected using air quality monitoring instruments provided. The necessary instruments and materials are scheduled and prepared in advance. This increases the efficiency of the data collection stage. The result will be compared with the simulation result and discussed in Chapter 4 as well.

Then, gathered data is assessed on the basis of the major variables. Several improvements employing simulation are being made at this stage in order to control or reduce the amount of dust in terms of particle matter within the factory, including varying the size or dimension of the factory's inlet and outlet, as well as modifying the location of the factory inlet and outlet. Each improvement will be discussed later in Chapter 4. This stage is repeated until the approved study results are achieved.

Last but not least, all the data studied, gathered and analyzed will be included in a full written report along with a comprehensive discussion of the results of this analysis.

3.2 Investigated Factories

One furniture manufacturing industry located in Ampang, Selangor is being selected as the investigated factories. From the small furniture manufacturer in the beginning of establishment, the factory today specializes in green furniture manufacturing as well as interior fit out and décor items It has been in operation since 1993 and employs a total of 25 people. The working hours is from 8.30am to 5.30pm during weekdays, 8.30am to 12.30pm on Saturdays and closes on Sundays.

These factories are involved in every step of the production process from turning raw materials into finished goods using tools, human labor and machinery. Several processes involve such as using Computer Numerical Control (CNC) milling machine to create shapes, slots, holes, notches, grooves, pockets, and specialty faces, and perform the machining process of manufacturing CNC milling parts. Then, wood planning which the process is using a thickness planer to trim or even out the wood to a consistent thickness throughout their length and flat on both surfaces. Next are wood cutting where this factory is using a sliding table saw for longitudinal and cross cutting of various kinds of wood-based panels. Lastly are sanding and polishing process in which the surface of the wood is rubbed gently using a sandpaper to remove all kinds of impurities before proceeding to the finishing phase which is painting and spraying.

3.3 Simulation Study

3.3.1 Geometry of computational model

Figure 3.3 shows the factory layout in 3-Dimensional form created using Solidwork. However, for the purposes of simplification and ease of research, this study will focus on the 2-Dimensional analysis only. The computational model for the factory was created based on the size of scale investigated factory where there are one inlet located in the entrance of the factory, two opening outlets at the top side wall of the factory and one main outlet located at the back of the factory as shown in the figure below. In order to have more accurate and reliable result, some bigger machines are being considered in this simulation study. As shown in the Figure 3.2, there are 4 machine that it is believe will be interrupt the flow of the air within the factory due to their size as well as the position inside the factory. The machine are CNC machine, wood planing machine and 2 table sliding machine which being labelled with 1, 2 ,3 and 4 respectively as shown in the figure below.

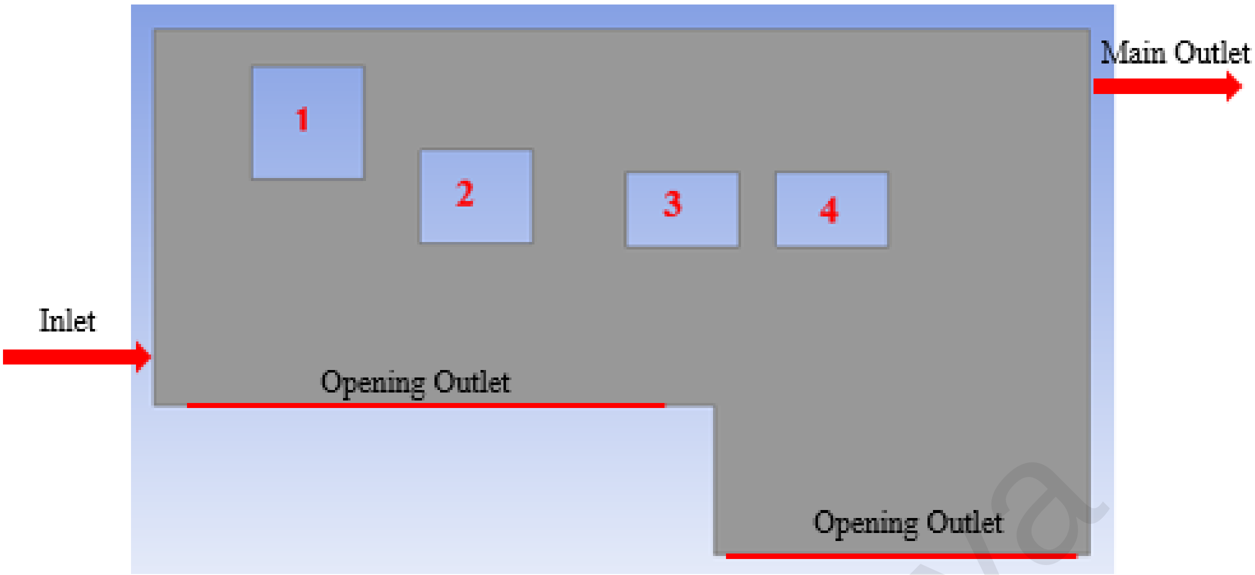


Figure 3.2: 2-Dimensional factory layout

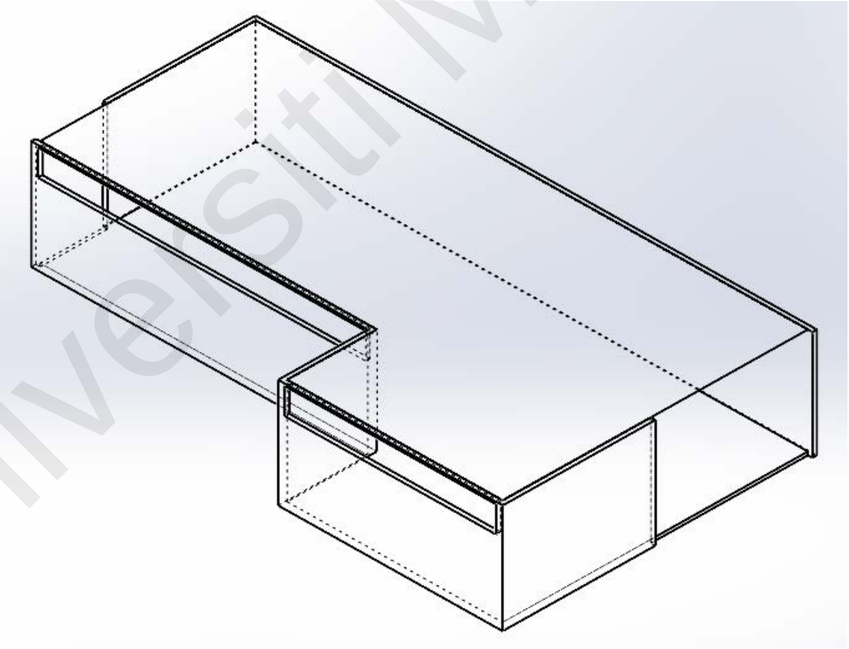


Figure 3.3: 3-Dimensional factory layout

3.3.2 Mesh Generation

The computational grids for the modeled geometry are set to have an element size of 1 m and refinement is imposed on the edges of each machine in order to have more finer meshes near the machines. As result, the total nodes and total element for the computational geometry are 37617 and 36371 respectively. Figure 3.4 shows the result of mesh on the geometry of computational model.

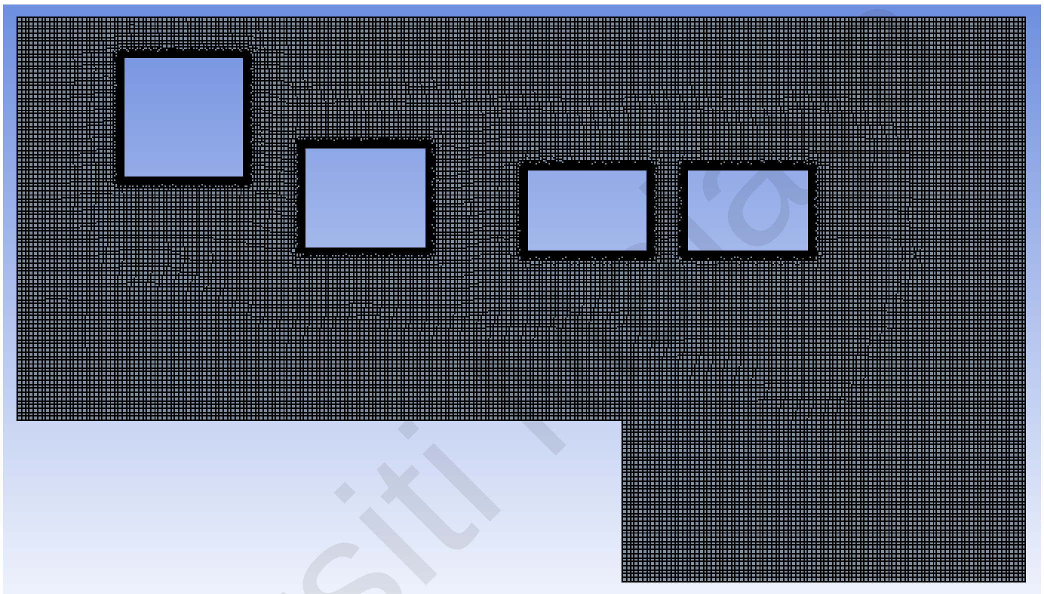


Figure 3.4: Generation of mesh

For this simulation study, the inlet and the outlet of the factory are set as shown in the figure below. Figure 3.5 depicts the inlet is set to be at the front site of the factory while Figure 3.6 shows the 3 outlet comprises of 2 opening outlets located at the side of the factory and 1 main outlet located at the end of the factory.

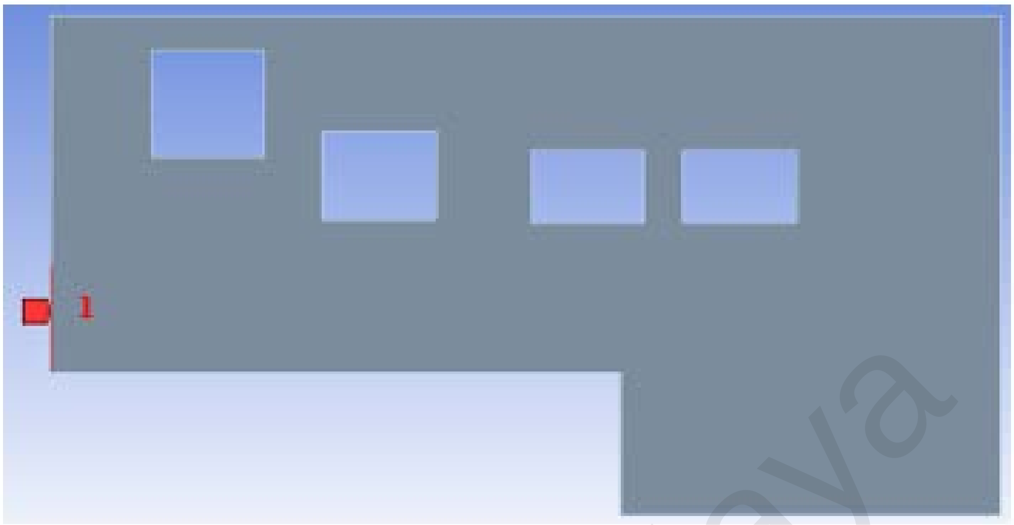


Figure 3.5: 1 Inlet boundary condition

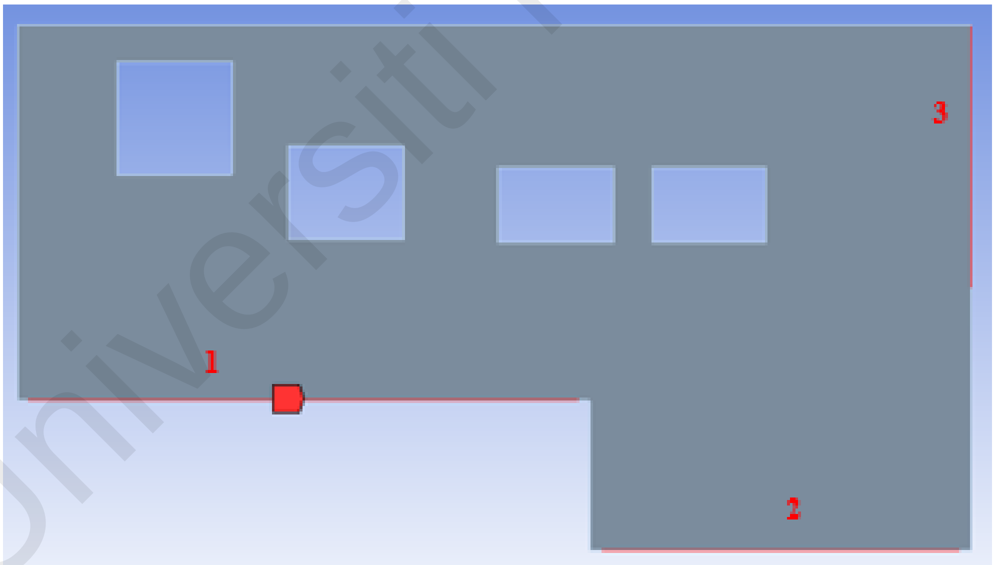


Figure 3.6: 3 Outlet boundary condition

3.3.3 Solution

The airflow in the within the factory followed the continuous medium hypothesis and the law of conservation of mass, momentum. The flow in this study was considered to be a *steady-state, incompressible, and two-dimensional turbulent flow*. A standard k-epsilon turbulent model was applied to show more reasonable results. The dust particles were spread throughout the airflow. As a result, the commercial CFD code ANSYS Fluent, which is based on the Euler–Lagrange equation, was developed.

Mathematical Model of Air Flow

Since the dust flow behaviour is strongly reliant on fluid flow, obtaining a flow field capable of simulating the real site circumstances is critical. The following is a representation of the continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

The Navier–Stokes equations can be expressed as follows:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_i}\left[(\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \tag{2}$$

where ρ denotes the fluid density, x_i and x_j denote the coordinates in the x- and y-directions, respectively, u_i and u_j denote the time-averaged velocity in the x- and y-directions, respectively. Meanwhile the effective turbulent pressure is denoted by p, the gravitational acceleration in direction i is denoted by g_i, and the coefficient of turbulent viscosity is denoted by μ_t

Equations (1) and (2) were converted into discretized algebraic equation form using the finite volume approach, which was implemented in Fluent. The physical variables of the airflow field at discrete places or volumes could thus be calculated using iterative numerical methods.

k- Epsilon model (k- ε model)

k-ε model is the most popular turbulence model used in computational fluid dynamics (CFD) to simulate mean flow characteristics for turbulent flow condition. It belongs to the Reynolds-averaged Navier Stokes (RANS) family of turbulence models which models all turbulence effects. It is a two-equation model that gives a general description of turbulence by means of two transport equations (partial differential equations, PDEs). Launder and Spalding (1974) developed the "standard" k-ε model, is one of the most established models for indoor as well as outdoor airflow simulation. k-ε Model is able to handle various fluid flow conditions. As it has simple format, strong performance, and also widely validate. In this model various improvisations has been conducted which results in better performance also make it more capable to handle various problem with simplicity. The turbulent eddy viscosity 'vt' in k-ε model is find with the help of following relation,

$$v_t = C_\mu \frac{k^2}{\varepsilon}$$

Where k representing kinetic energy, ε shows dissipation rate of kinetic energy in flow and $C\mu$ is constant coefficient

By considering the Malaysia's mean annual wind speed which is 2 m/s and the fan used within the factory therefore we assuming the velocity of the air is 5 m/s in total. Therefore 5m/s of velocity of the air are being set at the inlet of the factory.

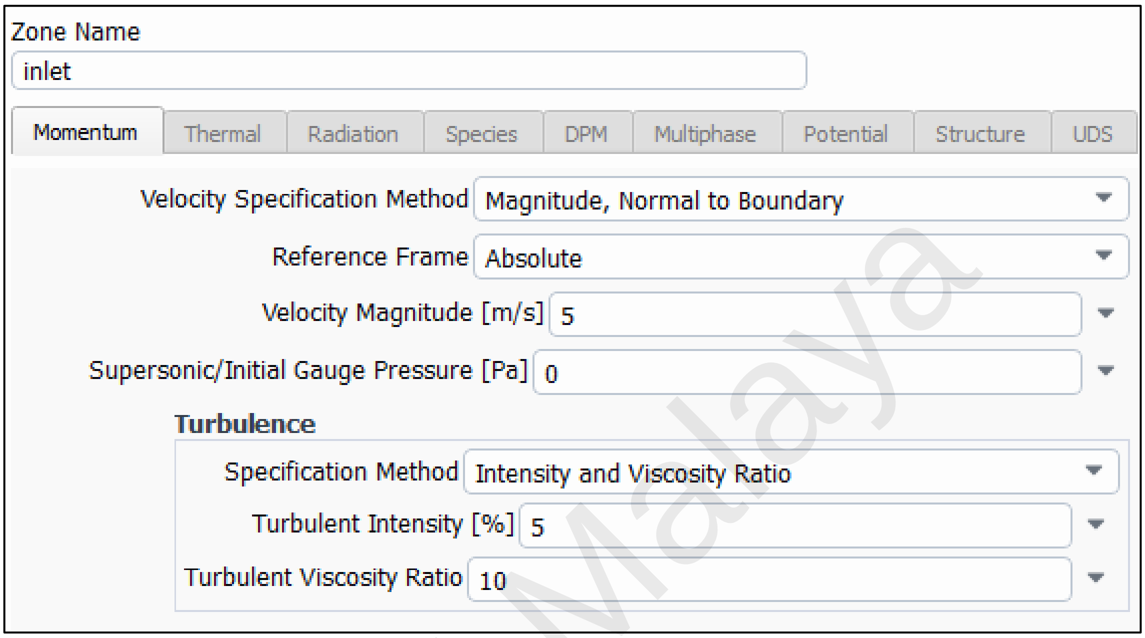


Figure 3.7: Boundary condition for velocity at inlet

Since the air moves from higher (positive) pressure regions to the lower (negative) pressures regions based on Bernoulli's principle phenomenon, which uses pressure differences to move air therefore we assume that the inlet of the factory have higher pressure than the main outlet of the factory. So, for the direction of the air, the air will flow from left (inlet) to right of the factory (main outlet).

Next, initialize by using *Standard Initialization* and set the analysis to be *compute from inlet.* Then run the calculation by setting the number of iterations to be 500. The calculation will be repeated until the solution is converge. Figure 3.8 shows the detail for the initialization method.

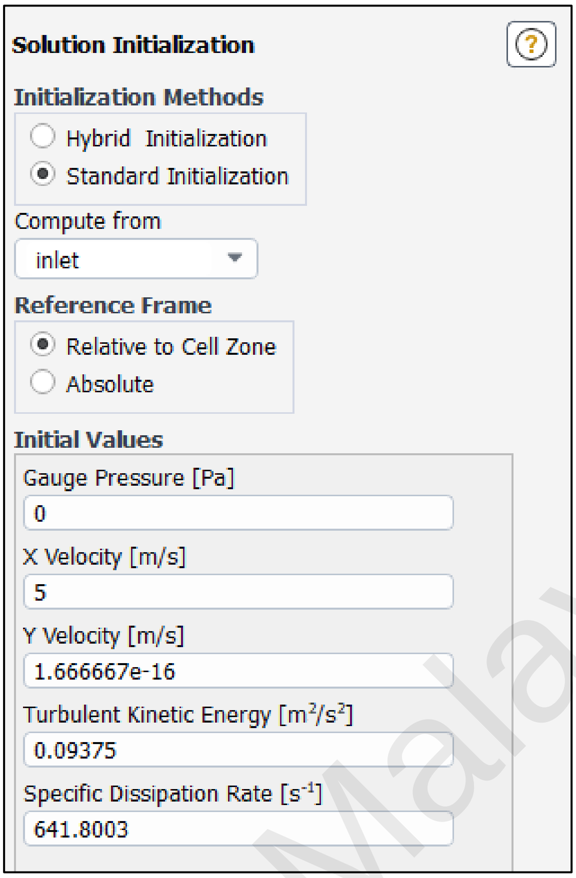


Figure 3.8: Initialization method

3.3.4 Result

Air velocity in the factory is a significant aspect in how well the air does its role of removing dust and travelling from one location to another within the factory out. Thus, velocity contour is then plotted with the detail are being set as follow and the result are being discussed later in Chapter 4.

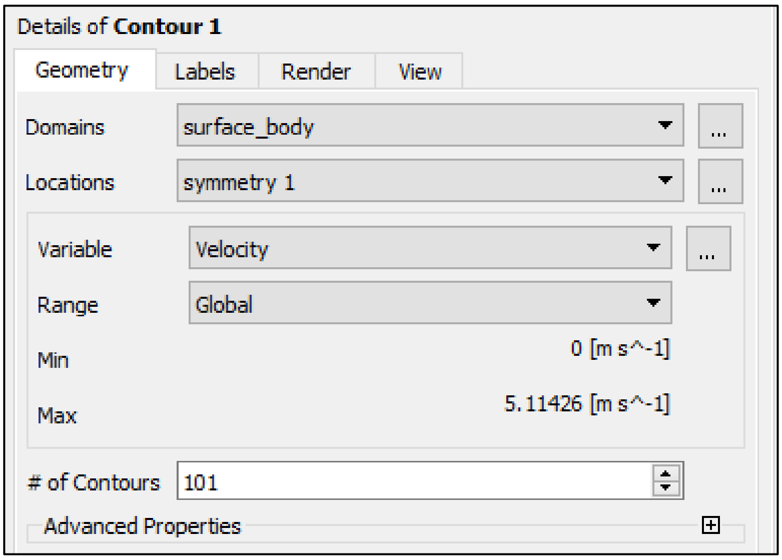


Figure 3.9: Velocity contour detail

3.4 Data Analysis

3.4.1 Sampling

As depicts in Figure 3.10 the floor plan of the factories are initially distributed into multiple squares. The sampling locations are then selected at random with respect to the squares, taking into account of office area and workstations. These locations are sampled for particulate matter readings. The locations are named using alphanumeric, where the numbers denoting the rows and letters denoting for the columns. Each reading is taken when the measuring device's reading is stable, which normally takes around 1 minute.

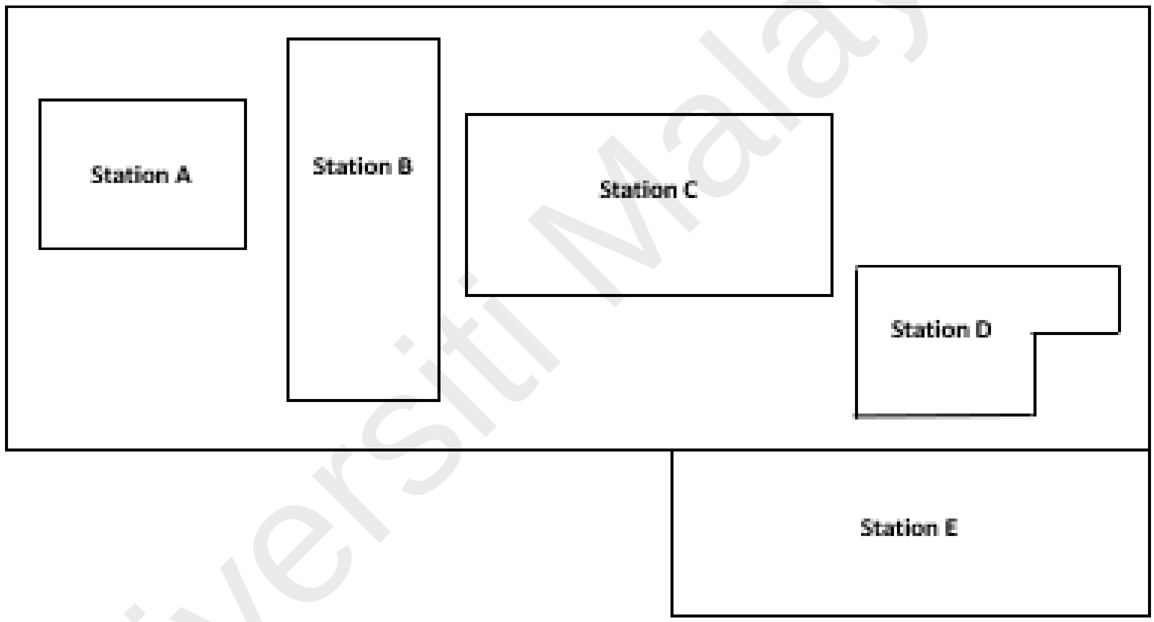


Figure 3.10: Sampling of floor plan in the factory

3.4.2 Instrumentation

Figure 3.11: BRAMC Portable 4-in-1 Air Quality Monitor

Figure 3.11 above is a handheld portable smart air quality detector called The BRAMC Portable 4-in-1 Air Quality Monitor. The instrument is pre calibrated before it is used for the sake of efficiency and quality assurance. BR-Smart Series is a real-time air quality monitoring instruments that uses a high-precision sensor used to detect air quality of indoor environment. It is capable of directly translating pollutant concentrations in the air into intuitive data in order to provide the users with the air quality monitoring information.

3.4.3 Experimental Data

After collecting data for the particulate matter, the mean values are calculated and the results are compared with the world health organization guideline (WHO, 2018) where the annual mean for PM2.5 (fine particulate matter) is 10 μg/m^3 and 24-h mean is 25 μg/m^3 while that of PM10 (coarse particulate matter) is 20 μg/m^3 and 24-h mean is 50 μg/m^3. These mean values were used to calculate the air quality index (AQI). According to the United States Environmental Protection Agency, the (AQI) is a daily air quality index. This index indicates whether the air we breathe is clean or harmful, as well as the level of concern and health repercussion (EPA, 2014). The AQI is concerned with "health impacts that may occur within hours or days of inhaling unhealthy air." Table 3.1 below shows the air quality index rating (Njoku et al., 2016). In addition, for PM2.5 and PM10, the table displays the AQI pollutant concentration particular range. The air quality is thought to be better when the AQI value is low.

Table 3.1: Air quality index (AQI) values, PM2.5 and PM10 conc. color codes, air pollutant level of health concern

AQI Value of Index	Levels of health concern	Particulate Matter Concentration (mg/m^3)		AQI Color Code	Air pollution level
		PM2.5	PM10		
0 – 50	Good	0 – 0.012	0 – 0.054	Green	Level 1
51 – 100	Moderate	0.0121 – 0.0354	0.055 – 0.154	Yellow	Level 2
101 – 150	Unhealthy for sensitive groups	0.0355 – 0.0554	0.155 – 0.254	Orange	Level 3
151 – 200	Unhealthy	0.0555 – 0.1504	0.255 – 0.354	Red	Level 4
201 – 300	Very unhealthy	0.1505 – 0.2504	0.355 – 0.424	Purple	Level 5
301 – higher	Hazardous	0.2505 – higher	0.425 – higher	Maroon	Level 6

The AQI is separated into ranges, which are then numbered and color-coded, with each color indicating the level of health concern and its significance. The ranges represent the level of health risk related with air quality, ranging from a healthy standard level of zero to a hazardous level of more than 300. Table 3.1 illustrates six major classifications, each of which is denoted by a color code, as well as levels of health concern and air pollution. Air pollution Level 1 denotes good and healthy air quality, since the air quality in this category is deemed satisfactory and poses little or no health risk.

Although level 2 air pollution is safe, certain persons (a very small number) may be at risk or have mild health concerns, particularly those who are normally susceptible to air pollution. Level 3 is considered unhealthy for sensitive peoples; while this level may not effect the general public, it does put persons with diseases like lung illness and heart disease, as well as vulnerable groups like children and the elderly, at danger. Level 4 pollution is considered unhealthy; certain members of the general public may experience negative health effects, while sensitive groups may face more serious health difficulties.

Level 5 with the color code purple is extremely harmful to the general public and will result in a health alert, as the danger of health impacts is increased for everyone and is more serious at this level. Finally, level 6 air pollution is associated with a high risk of health effects, and this level of pollution will result in a health warning of emergency situations, since anyone or the entire exposed population is more likely to be harmed.

3.4.4 Heatmap

Then for every station, heatmap is done to identify which region of the station have the least and the most pollutant. Generally, the purpose of heatmap is to further visualize the data collected and is plotted with respect to the floor plan of the site. From this heatmap, we can identify the location with high concentration by observing the color intensity. The higher color intensity (darker) will indicate that the location have higher concentration compared to other location which have lower color intensity (lighter).

3.5 Proposed Remedies and Improvement

The remedies are designed and proposed using a same software of Ansys Fluent. Three modifications in overall is applied on the original layout of factory. For the first two modification, the study will focus on the inlet and the main outlet of the factory. The opening outlet that have been created by the factory as their alternative in removing the dust out from the factory is keep as fixed variable throughout the simulation. The main focus is to study the effect of size and the location for both inlet and main outlet on the velocity as well as the distribution of the air flow within factory. Hence, this will provide an indication on how the dust generated during production hour will be eliminated out as it follow the movement of air that travel from the inlet to the outlet. For the third modification, an addition of inlet opening near painting and spraying area (Station E) is proposed to solve a larger zero velocity area problem that exist from the simulation study which could contribute to higher reading of particulate matter concentration. An improvement will be done on the model shown in the Figure 3.12.

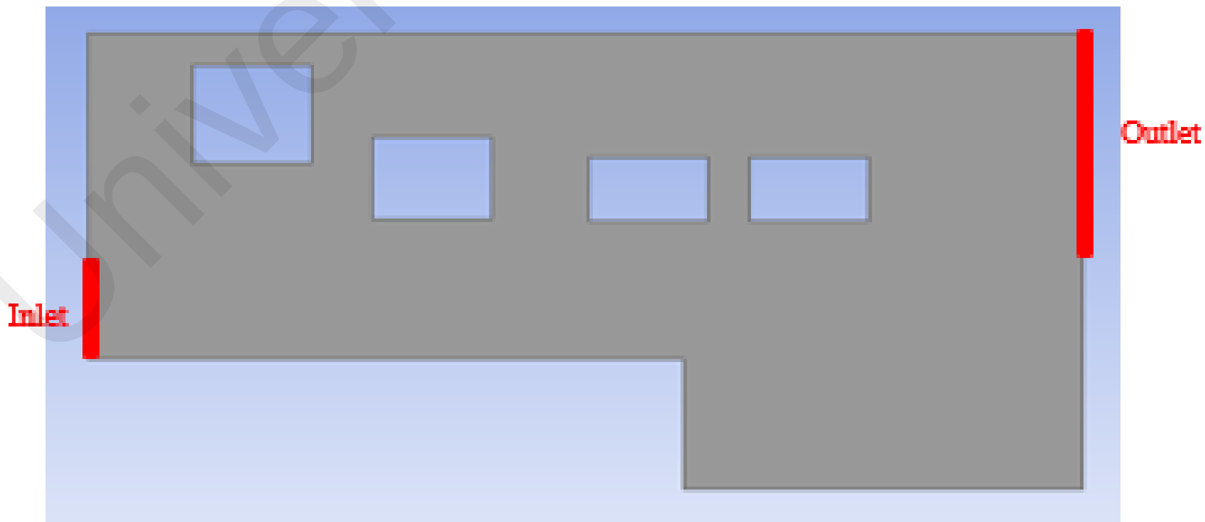


Figure 3.12: Size and the location of inlet and main outlet for unmodified factory

CHAPTER 4: RESULTS AND DISCUSSION

This chapter consist of 3 subsections. The first subsection of the chapter contain the simulation study in which the airflow within the factory is simulated in order to investigate movement of the dust particle generated during the manufacturing process as the dust will be eliminated from the factory with the flow and the movement of the air. Therefore, the simulation is focusing on the air flow presence in the factory. The velocity contour for the original dimension of factory is being plotted and discussed in this subsection.

The chapter then moves to the second subsection, which contains the experimental data recorded for the concentration of particulate matter from various sites within the factory, as validation for the simulation performed in the first subsection. The factory is divided into 5 different locations with different process and purposes for each workstation. The location involve are CNC process which denoted as Station A, wood planing area which denoted as Station B, cutting area denoted as Station C followed by sanding, polishing, and smoothing area which denoted as Station D and finally is finishing area (painting and spraying) as Station E.

In the last subsection, several improvement using the simulation is being done on the factory in order to control or reduce the amount of dust in term of particulate matter within the factory.

4.1 Estimation Study via Simulation

Figure 4.1 illustrates the simulation for the air flow within the factory with the original scaled dimension without any modification where the inlet is measured to be smaller than the main outlet of the factory while the location for both inlet and outlet are in the corner of front and end factory respectively.

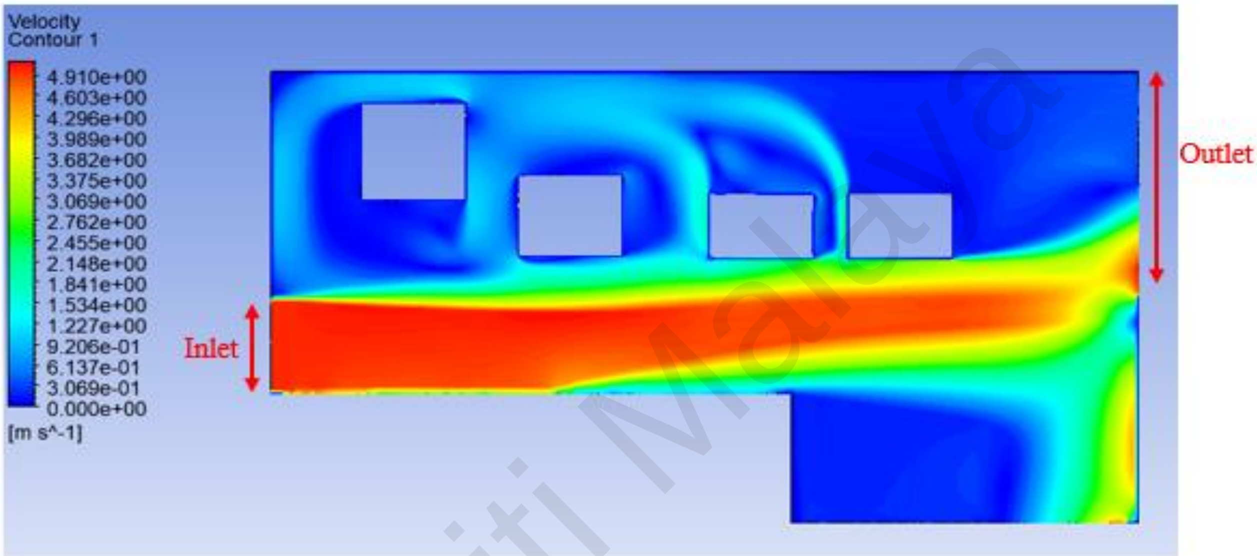


Figure 4.1: Velocity contour on the original scaled of investigated factories

From the velocity contour analysis, the red color indicates that the location is having a highest velocity meanwhile the blue color indicates the absence of velocity at the location. In the legend view of the velocity contour, there are also presence of others color as the color is vary depending on the amount of velocity available on the location. Thus, by the distribution of color in the figures above, the velocity of air flow can be observed visually. Air flow velocity generally decreased from left to the right. From the result, the red contour tend to occur near the inlet as well as the opening outlet that have been created by the factory initially. Meanwhile much area near the main outlet at the end of the factory show a blue contour. Despite the fact that the operational area's air inlet speed was higher than the non-operating areas, there was still a lot of air following into the equipment directly from the non-operating area, and this part of the air did not play a role in carrying pollutants away. This is due to the presence of some larger and more significant machines, such as CNC machines, wood planing machines, and cutting table saws, which hinder the flow of air from reaching the factory's end and being eliminated. Generally, when moving air encounters an obstacle, its path narrows as it flows around the object. Regardless, the amount of air travelling past each location in the airflow at any given time is the same. The air must either compress or speed up where its flow narrows in order for this to happen.

As can be seen from the simulation result, a small amount of velocities acting on the machine suggest that only some of the dust generated during the production hours will follow the movement of the air while majority of the dust will be accumulated near the machine. However, some of the machines are equipped with the ventilation system, therefore it help in reducing the value of the particulate matter reading that will be discussed later in experimental reading subsection. Painting and finishing site also can be considered as the critical location as there are almost no velocity are presence on the area which may lead for the dust generated to be accumulated at the location.

As overall range of the velocity throughout the factory are between 0m/s and 4.91 m/s where the higher velocity tend to occur at the inlet and the opening outlet near the inlet meanwhile the location with machine and site E have the lower velocity. Even so the simulations performed are merely for the purpose of estimation and will be compared to experimental data for validation purposes later.

4.2 Experimental Data

In this part, experimental data for the concentration of particulate matter from different locations within the factory is recorded using the handheld portable smart air quality detector. Data recorded for PM concentration for each station with different process is tabulated in table 4.1 which ranging from lowest to highest concentration values.

Table 4.1: Experimental data recorded for each workstation

Workstation	Range of Particulate Matter Concentration (mg/m^3)
Station A	0.163 – 0.263
Station B	0.258 – 0.354
Station C	0.155 – 0.274
Station D	0.024 – 0.131
Station E	0.057 – 0.191

From the table above, the highest range of PM10 concentration is recorded in Station B while the lowest range of PM10 concentration value is recorded in Station D. The explanation behind each data recorded for every station will be discussed later in the next subsection. For each of the station, the graph of PM10 concentration vs locations within the factory is plotted and the heatmap for each of the station is done.

4.3 Particulate Matter (PM10) Concentration

4.3.1 Station A - CNC

Figure 4.2 depicts the concentration of particulate matter with particle size less than 10µm (PM10) at 16 locations in Station A which consists of CNC machine. From the figure, it shows that 11 location is fall into level 3 of air pollution level (orange) while the remaining of 5 location is fall into level 4 of air pollution level (red).

According to the tabulated data, the locations with the red colour that signify as 'unhealthy' according to World Health Organization (WHO) guidelines are A-B1, A-B2, A-B3, A-C2, and A-C3, where higher readings of PM10 concentration ranging from 0.256 to 0.263 mg/m^3 were recorded at these locations. Meanwhile, the orange-colored locations that signify 'unhealthy for sensitive groups' are A-A1, A-A2, A-A3, A-A4, A-B4, A-C1, A-C4, A-D1, A-D2, A-D3, and A-D4 with PM10 values ranging from 0.163 to 0.212 mg/m^3.

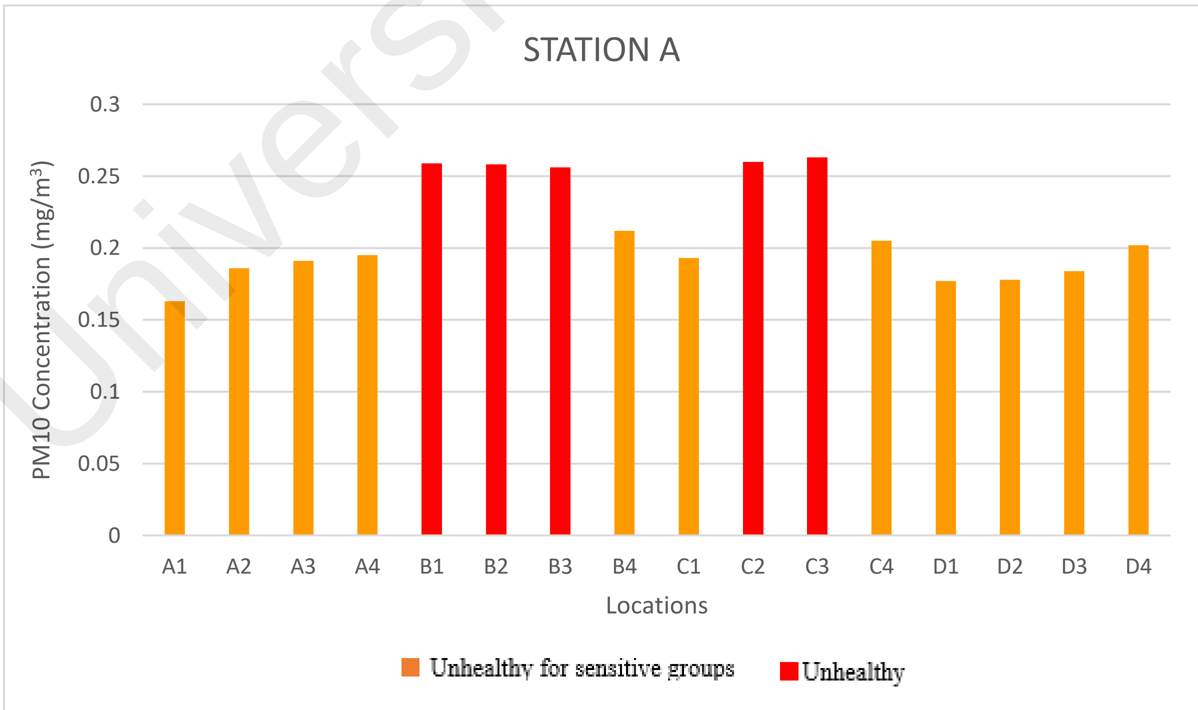


Figure 4.2: Graph of Particulate Matter Concentration against Locations in Station A

The heatmap for Station A is shown in Figure 4.3. Locations with high PM10 concentration are frequently related with the purposes of the workstations. The type of machine and way of processing influence increases in the dust concentration in the air (Kos et al., 2004). Station A is consisting of CNC machine. Despite the fact that the machine was equipped with the dust collector system however, the amount dust generated during production hours is significant. When the working zone is large and the tool moves over long distances during processing, dust removal becomes challenging. This happens in the majority of CNC machines used in the woodworking sector (Varga et al., 2006).

As according to Dessange, dust generated during routine wood machining processes may not be completely captured by machine-integrated devices and hence can be dispersed and distributed throughout the factory (Dessagne et al 2006). In this regard, the dispersion of chips in various directions throughout the treatment zone is quite undesirable. Many chips are still not removed when the movement direction of the chips formed during machining does not correspond with the air suction created by an extraction system, and they can become scattered in the air surrounding the machine. This occurs during drilling when the entire tool penetrates the work piece deeply. For this reason, there are problems with the direct removal of chips from working tools. Chips are dispersed in all directions also as a result of the high-speed rotation of those tools.

	A	B	C	D
1	0.163	0.259	0.193	0.177
2	0.186	0.258	0.260	0.178
3	0.191	0.256	0.263	0.184
4	0.195	0.212	0.205	0.202

Figure 4.3: Heatmap of Particulate Matter Pollutants in Station A

4.3.2 Station B - Wood Planing

Figure 4.4 shows the graph of PM10 concentration against 20 locations in Station B in which the wood planning process is being run at this station. According to the permissible exposure limit (PEL) regulated by the Department of Occupational Safety and Health (DOSH), the range values of PM10 between 0.255 – 0.354 mg/m^3 are consider as unhealthy area (Saad et al., 2017). From the graph, it shows that this station is fall under level 4 of air pollution with all the location within this station is categorized into unhealthy area where the exposure workers may experience negative health effects while sensitive groups of workers may face more serious health difficulties if expose to this area for an extended period of time.

The location that have the highest value of PM10 concentration is B-B6 with the value of 0.354 mg/m^3 while location of B-A2 have the lowest value of PM10 concentration which is 0.258 mg/m^3.

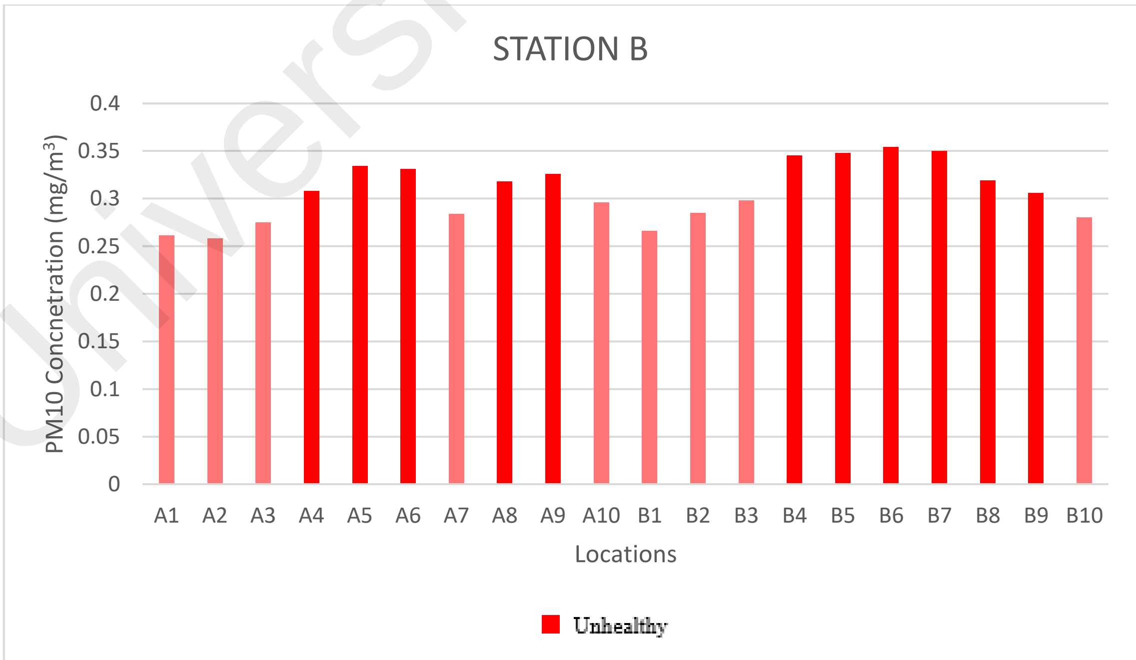


Figure 4.4: Graph of Particulate Matter Concentration against Locations in Station B

The location with the higher color intensity (darker red) indicate that the location is having much more PM10 concentration which is more than 0.300 mg/m^3 compared to others location with the lower color intensity (lighter red). From the heatmap in Figure 4.5, it shows that there are 11 locations within the station which have higher color intensity which are B-A4, B-A5, B-A6, B-A8, B-A9, B-B4, B-B5, B-B6, B-B7, B-B8 and B-B9 with the value ranging from 0.306 mg/m^3 up to 0.354 mg/m^3. For the location with lower color intensity, there are total of 9 locations which are B-A1, B-A2, B-A3, B-A7, B-A10, B-B1, B-B2, B-B3 and B-B10. Furthermore, there is no suction pump around the work piece, causing the level of PM10 pollutant here to be hazardous due to unsatisfactory dust removal (Yuan et al., 2014).

Station B is considered as the unhealthiest region or area inside the factory due to absence of good ventilation system as compared to other machine that usually produce more dust such as CNC machine and sliding table machine in station A and station C respectively. This is because those machines had been equipped with dust removal system. Due to original system poor dust capture performance, dust inevitably would flow toward the worker around the wood planing machine. Therefore, it is recommended that the operator wear a mask and take other safeguard procedures to minimize the exposure chance.

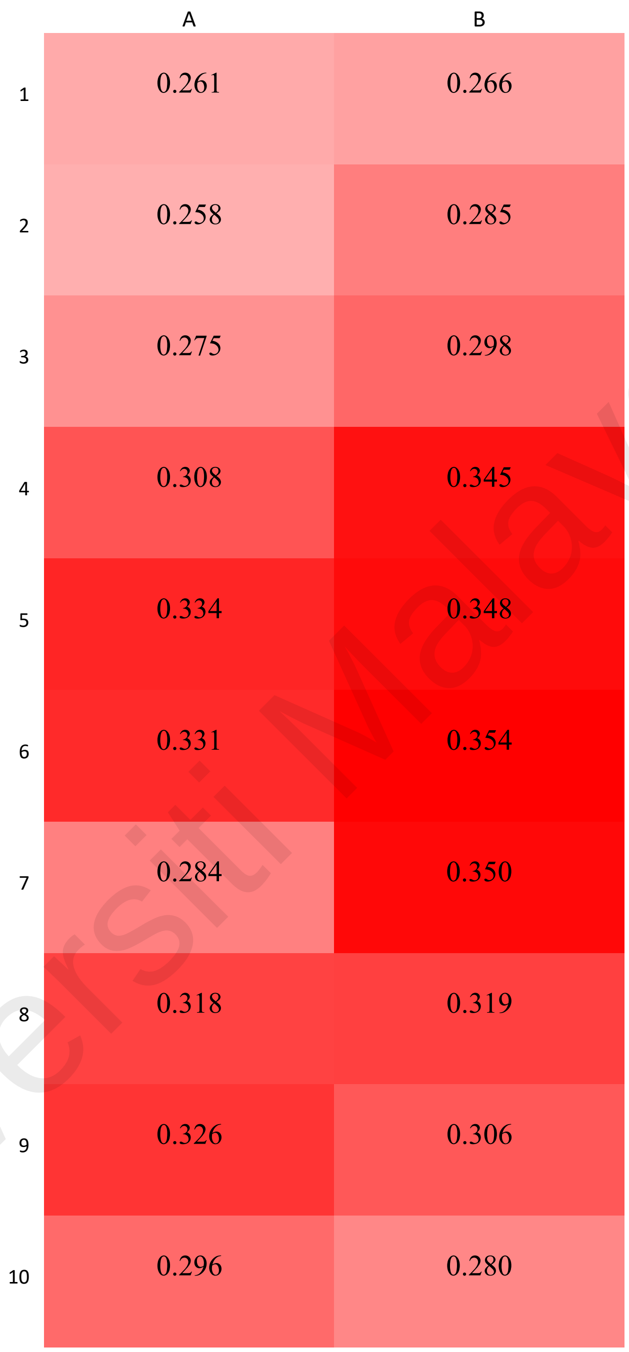


Figure 4.5: Heatmap of Particulate Matter Pollutants in Station B

4.3.3 Station C - Cutting

Figure 4.6 exhibits the graph of PM10 concentration against 30 locations in Station C which are cutting process. From the figure, it shows that only 7 location is fall into level 4 of air pollution level (red) with C-C3 having the highest value which 0.274 mg/m^3 of PM10 concentrations had been recorded in this location followed by C-B3, C-C2, C-D3, C-C4, C-B4, C-B5, C-D4 locations with the value of 0.268, 0.267, 0.265, 0.262, 0.257, 0.257 and 0.255 mg/m^3 respectively.

While the remaining of 23 location is fall into level 3 of air pollution level (orange) that indicate as unhealthy for sensitive group which mean it only put persons with diseases like lung illness and heart disease, as well as vulnerable groups like children and the elderly, at danger but not gives effect for general public. At this level, the station recorded the value of PM10 concentration vary from 0.155 to 0.216 mg/m^3.

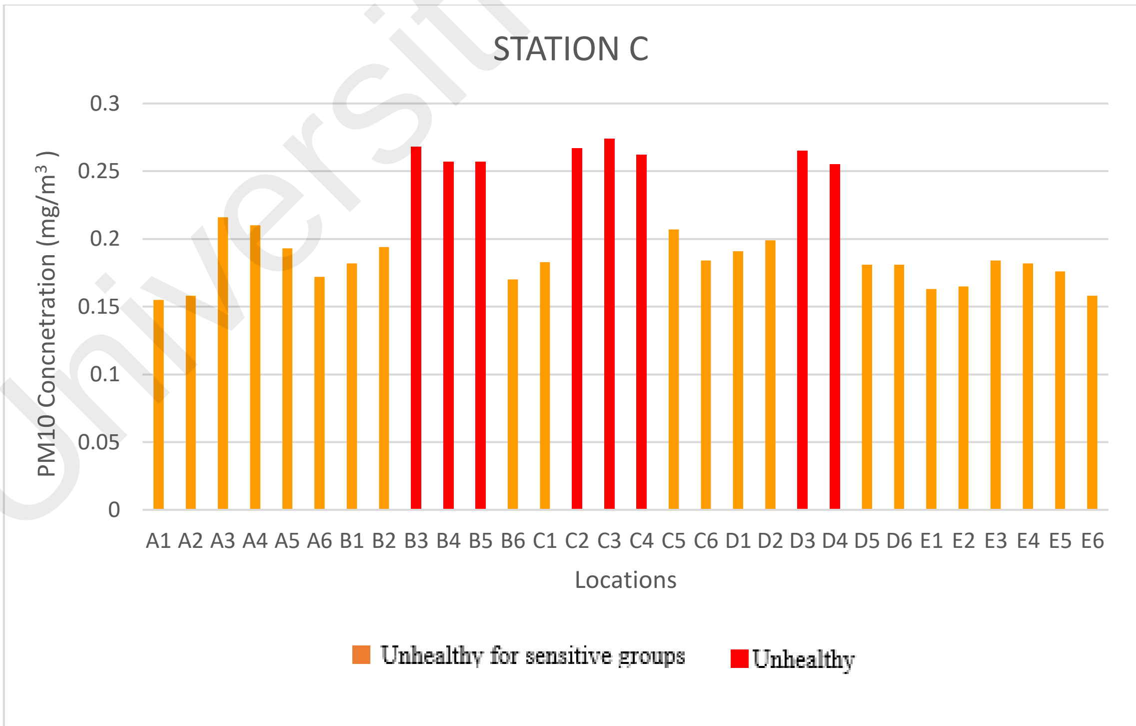


Figure 4.6: Graph of Particulate Matter Concentration against Locations in Station C

The pattern of locations with higher values of PM10 concentration (red) likely to be in the center of Station C, as shown in the heatmap from Figure 4.7. The explanation behind this are since there are two saw sliding table machine is available in the station, therefore, as both machine is running simultaneously, the combination of the wood dust produced from each of the machine will be combine and meet in between the machine and eventually will lead to higher value of PM10 concentration. As can be observed, C-C3 which is located in the middle of the station have the darkest red in color compared to others location which indicate the locations have the highest concentration of PM10.

Other reasons are the cutting parameter. Cutting parameters can influence the chip thickness and resulting dust emission and surface quality during wood machining (Ugulino & Hernández, 2017). Thus, it is believe the parameter of cutting such as cutting velocity, depth of cut, spindle speed and feed rate may contribute to the higher concentration of particulate matter within the station.

	A	B	C	D	E
1	0.155	0.182	0.183	0.191	0.163
2	0.158	0.194	0.267	0.199	0.165
3	0.216	0.268	0.274	0.265	0.184
4	0.210	0.257	0.262	0.255	0.182
5	0.193	0.257	0.207	0.181	0.176
6	0.172	0.170	0.184	0.181	0.158

Figure 4.7: Heatmap of Particulate Matter Pollutants in Station C

4.3.4 Station D – Sanding/ Polishing/ Grinding

The tabulated data for Station D demonstrates that the station has the lowest value of PM10 concentration among the station discussed in this chapter with the concentration value of PM10 not even exceed 0.150 mg/m^3. Therefore, it can be considered as most healthy area since the station is not contribute to the higher value of PM10 concentration within the factory. The location within the station is fall under two level of air population only which is level 1 and level 2. The location that fall under level 1 of air pollution (green) and denotes as good condition area are D-A4, D-A4, D-A6, D-C1, D-C5, D-C6, D-D1 with the value range in between 0.024 to 0.053 mg/m^3.

Meanwhile for location fall under level 2 of air population (yellow) which indicate moderate area, D-C3 shows the highest value with 0.131 mg/m^3 while D-B6 shows the lowest value for this level of air population with value of 0.056 mg/m3. For others location such as D-A1, D-A2, D-A3, D-B1, D-B2, D-B3, D-B4, D-B5, D-C2, D-C3, D-C4, D-D2 and D-D3, the value is ranging in between 0.062 mg/m^3 to 0.128 mg/m^3.

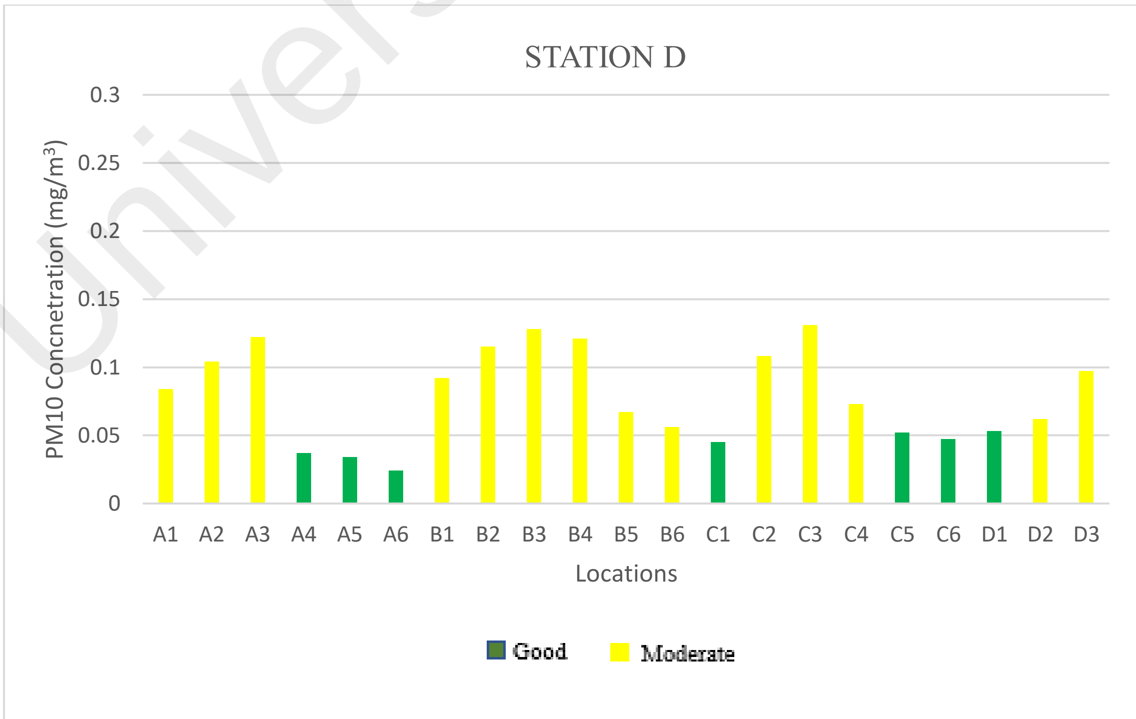


Figure 4.8: Graph of Particulate Matter Concentration against Locations in Station D

Places with high PM10 concentration are often associated with workstations such as sanding and routing (Ratnasingam et al., 2019). Sanding is widely recognized as one of the most frequent surfacing methods for preparing wood surfaces prior to coating. However, this process produces finer dust compared with other machining process (Chung et al 2000). Meanwhile grinding process eventually should be released from the sandpaper to keep the sand tool efficiently working. In fact, it has been discovered that the main dust produced in the course of sanding processes is silica, which has been linked to occupational disease (Dalin et al., 2005).

Unfortunately, no machines such as a sanding master machine, profile sander machine, or drum sander machine are observed in these areas, as the sanding operation is carried out manually by the workers. For this reasons, Station D had been regarded as the healthiest area within the factory. Another reason also is that the location of the station which located near the main outlet at the end of the factory therefore the dust generated will naturally been remove easily from the factory with the passage of air. D-B3 with the high color intensity (darker yellow) being the location with the highest PM10 concentration however the value is still in the moderate category while D-A6 depicts the lower color intensity among others (lighter green) indicating the location is the safest area for the workers as shown in Figure 4.9.

	A	B	C	D
1	0.084	0.092	0.045	0.053
2	0.104	0.115	0.108	0.062
3	0.122	0.128	0.131	0.097
4	0.037	0.121	0.073	
5	0.034	0.067	0.052	
6	0.024	0.056	0.047	

Figure 4.9: Heatmap of Particulate Matter Pollutants in Station D

4.3.5 Station E – Painting & Spraying

The PM10 concentration at 12 locations at Station E, which is a painting and spraying region, is exhibited in Figure 4.10. As overall, Station E is fall into level 2 and level 3 of air pollution level. Total of 6 locations are classified as level 3 (orange) category which indicate the area are unhealthy for sensitive groups. The area are E-A1, E-A2, E-A3, E-B1, E-B2 and E-B3 with the value 0.184, 0.191, 0.175, 0.167, 0.159 and 0.156 mg/m^3 respectively. While for the remaining of 6 locations which consists of E-C1, E-C2, E-C3, E-D1, E-D2, and E-D3 are classified as level 2 (yellow) category which indicate the area are 'moderate'. The value is ranging in between 0.063 up to 0.143 mg/m^3.

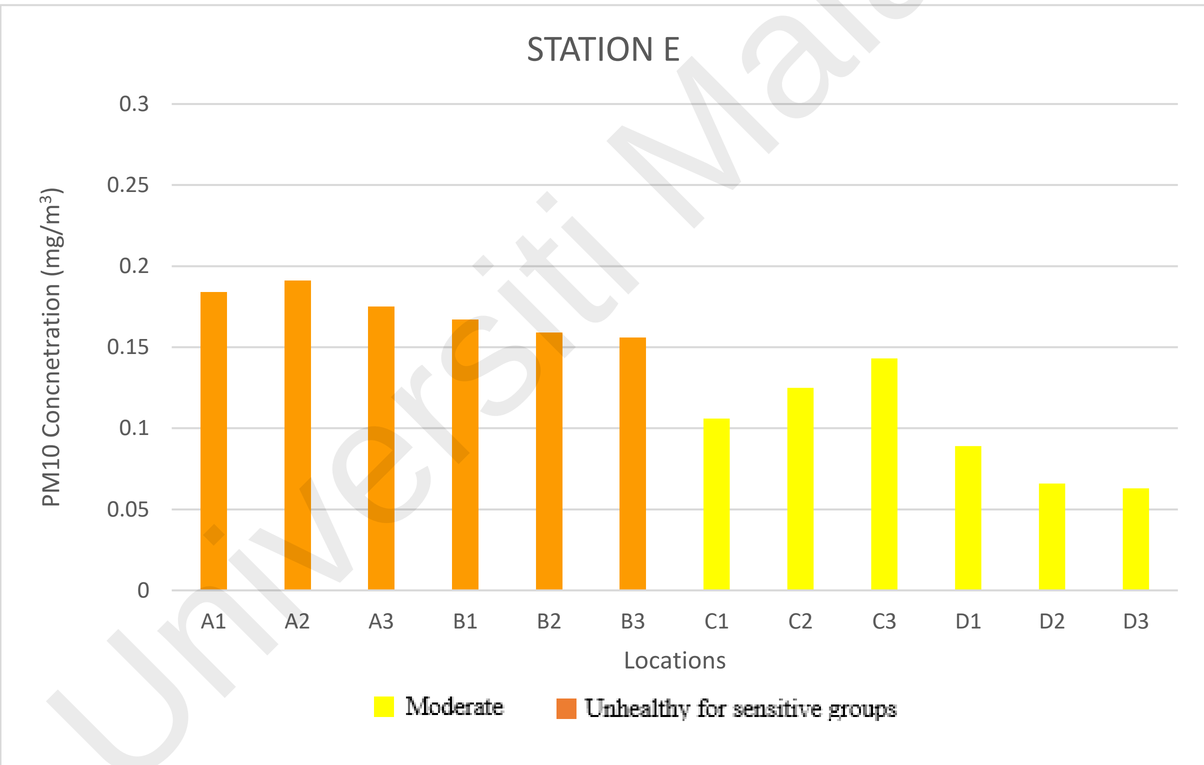


Figure 4.10: Graph of Particulate Matter Concentration against Locations in Station E

The highest value of PM10 concentration in this station can be observed at the end of the station which is E-A2. The location has the high color intensity (darker orange) as compared to others due to poor air ventilation on that area. As shown by the simulation study in the first subsection of this chapter, it show that the zero-velocity area tend to occur on the left part of the station where the dust are accumulated on that area. Therefore, it is proof by the heatmap in Figure 4.11 as the result depicts that the left of station have higher color density than the right area of the station. While the location such as E-A3, E-B3, E-C3, E-D3 have lower color intensity (lighter yellow) which indicate the location have lower value of PM10 concentration as illustrated in the heatmap below. This is due to the location that situated near the opening outlet area where the PM10 generated will be get rid of through the opening outlet immediately with the assistance of a standing fan.

Generally, paint application by spraying is the most popular method in industry, for two main reasons: (1) it results in a uniform distribution of paint, and (2) it can deliver very small amounts of paint. However, paint particles emitted from painting process can also leads to high PM10 concentration (Lai & Yan, 2016). These metal-containing paint particles have various sizes and those with particle size less than 10µm contributes to the PM10 concentration. According to study also cancer risks of carcinogenic metals (Cd, Ni and Cr) in PM10 for paint spraying process workers at the industrial ventilation equipment manufacturing plant nevertheless exceeded 10^{-6} indicating that a carcinogenic health effect existed in the spray-painting workplace.

	A	B	C	D
1	0.184	0.167	0.106	0.089
2	0.191	0.159	0.125	0.066
3	0.175	0.156	0.143	0.063

Figure 4.11: Heatmap of Particulate Matter Pollutants in Station E

4.4 Simulation Study – Room of improvement

A. Effect of variation in Dimension for Inlet and Main Outlet

The first modifications we focus for the improvement are the size of the inlet and the main outlet of the factory while the size for the 'opening outlet' are kept the same. This is done by vary the wide of the inlet as well as the main outlet of the factory. By refer to the dimension, the original layout of the factory have the smaller inlet as compared to the main outlet. For this improvement, there are several situations proposed. The situations are:

i. Inlet is bigger than the main outlet
ii. Main outlet have the same wide as inlet
iii. Inlet have the same wide as main outlet

The result of analysis for each of the proposed situation will be discussed later. The improvement which give the least blue contour result (zero velocity) of airflow simulation within the factory are likely to be select. At the end of this section, one improvement will be selected to undergo the second modification which is the effect of different location for the inlet and the outlet.

Figure 4.11 represents the layout of the factory with the first situation of modification (A1) where the inlet of the factory is bigger than the main outlet. From the contour result, the velocity contour with blue color (no velocity) area are reduced in comparison to the result of velocity contour for original layout of the factory which show large area with the blue contour (stagnant area) that had been discussed in the first subsection of this chapter. Even though the value of velocity is small in some location such as near the machines, however the result show the increase in the velocity value of the air flow than before. Nevertheless, the effectiveness of the ventilation would be impeded if the inlet area were more significant than the outlet area. By referring to the continuity equation $A_1 v_1 = A_2 v_2$ where A is area while v is velocity, we can see that as area reduces, the velocity will increase. As a result, the smaller area of the main outlet will result in a higher velocity as we move from the inlet to the outlet. As shown in the figure, the highest velocity achieved is about 7.09 m/s. An unbalanced system would be created if the air that was coming in was higher than was going out.

Next, the main outlet have the same wide as inlet is shown in figure 4.12 where this is considered to be the second situation of modification (A2). The main outlet is modified to have the same size or dimension as inlet of the original layout of the factory. This mean both having a small opening for the air to travel within the factory. From the result, it show the improvement as the blue contour region is getting lesser than the first situation. Only for the station E there are still large area of zero velocity. The flow of the air is considered to be smooth as both inlet and outlet have the same size of opening. However, the size for both inlet and outlet is too small which can cause air resistance to be increase. Therefore, the force acts in the opposite direction to an object moving through the air which in this situation is dust or particulate matter to be higher and making it harder to remove the dust out from the factory due air resistance causes moving objects to slow down. As the result, the velocity is decreasing gradually as we go from inlet to the outlet.

For the last situation (A3) under the same factor of modification which is of variation in dimension for inlet and main outlet, Figure 4.13 depicts the inlet have the same wide as main outlet. This means inlet of the factory is modified to have the same size or dimension as main outlet of the original layout of the factory indicating that both having a large opening for the air to travel within the factory. If the inlet and outlet areas are large, then more air can travel through, more dust can eliminate out the factory. Other advantages include the ability to remove more heat at the same time. Preferably, an equal amount of airflow volume going into a building as exiting the building is the ideal outcome for a smooth and uniform flow of air.

In addition, as stated by Seifert at. al in one study discovered that when the openings are sufficiently large, the upwind mean kinetic energy is not totally lost when air flows approach these openings (Seifert et al., 2006). The speed is also can be considered consistent and stable throughout the factory as proved by the velocity contour which show an uniform yellow color as we go from inlet to outlet and only red color (high velocity) present in some location. As compared to 2nd situation (A2) even though it also shows uniform contour of velocity however the third situation have the highest uniform velocity which tell us the dust have the higher possibility to be eliminate out from the factory faster than the 2nd situation (A2).

Air flow by its very nature always seeks out the path of least resistance. When faced with multiple options for entering or exiting a building, the air will flow through the largest hole that offers the least resistance. The optimum conclusion is for there to be an equal amount of airflow volume entering and leaving a building. An imbalance of air flow across interior or exterior walls, ceilings, and floors can also cause pressure differences. Imbalanced air flow can occur if the supply and return to an area are not equal. From the result and explanation, the third situation of modification (A3) is selected to undergo the 2nd modification which is the effect of location for inlet and main outlet due to less of zero velocity area, uniform and even velocity distribution as well as smooth flow of the air throughout the factory.

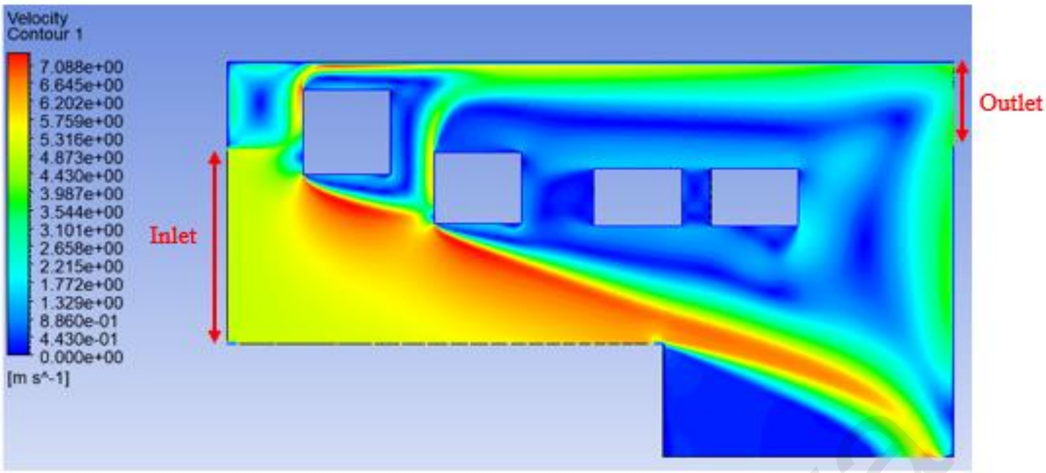


Figure 4.12: Inlet is bigger than the main outlet (A1)

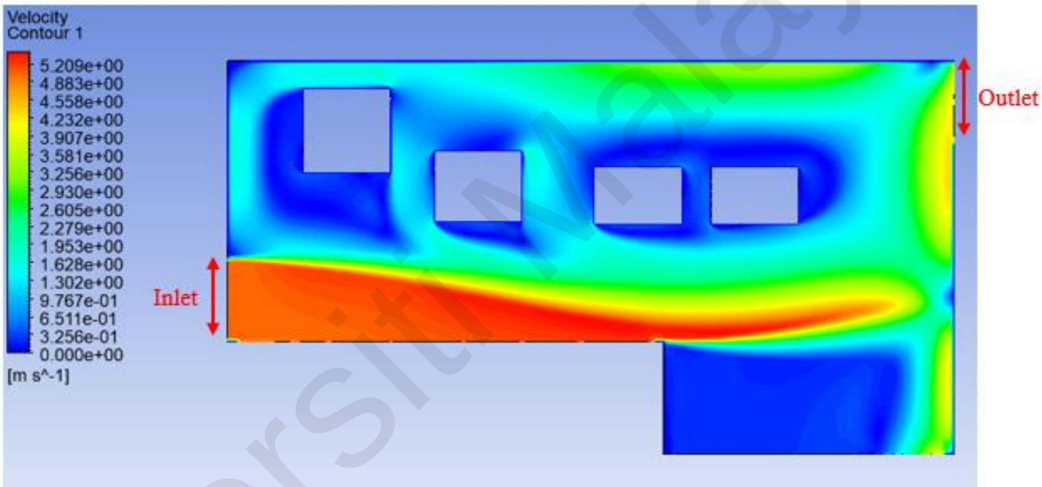


Figure 4.13: Main outlet have the same wide as inlet (A2)

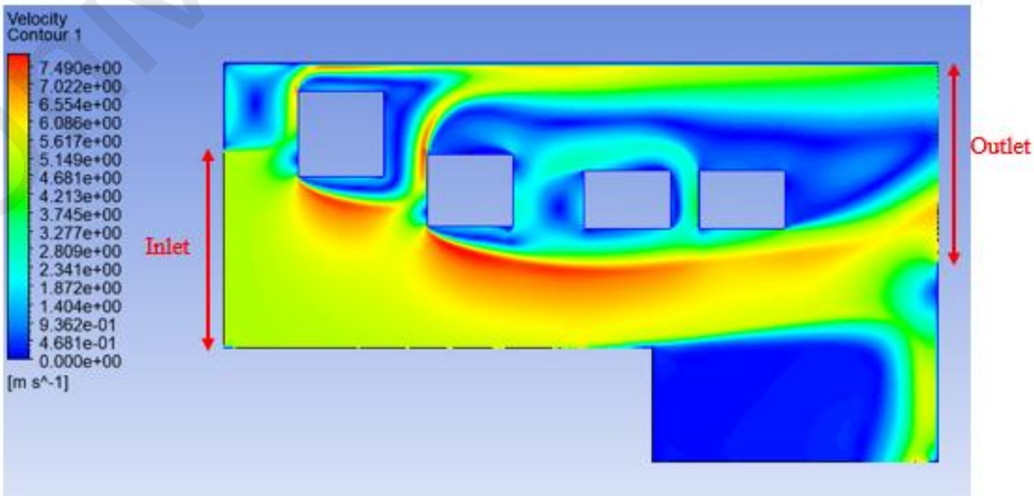


Figure 4.14: Inlet have the same wide as main outlet (A3)

B. Effect of different Location for Inlet and Main Outlet

Then, from the first modification which is the effect of dimension of inlet or outlet, *improvement A3* are being selected to be the best solution. Then we further improve the solution by considering the second modifications which is the effect of different location for the inlet and the main outlet of the factory while the location for the 'opening outlet' are kept at the same place. Bear in the mind, the original location for both inlet and outlet initially are located at the corner of front and end the of the factory respectively. By using the dimension of *improvement A3* model in the first part of discussion for the inlet and outlet of the factory previously, we proceed by study the effect of location for inlet and main outlet which are vary according to the situation listed below:

i. Inlet at the front middle of the factory, outlet at end corner of factory
ii. Inlet at the front middle of the factory, outlet at end middle of factory
iii. Inlet at the front corner of the factory, outlet at end middle of factory

Later on, the analysis results for each of the given situation will be described. The improvement which give the least blue contour result (zero velocity) of airflow simulation within the factory are likely to be chosen. At the end of this section, one improvement will be selected to undergo the last modification which an addition of inlet in painting and spraying area, Station E

For the first situation of modification (B1), Figure 4.14 shows the location of the inlet is modified to be located at the middle of front factory while the location for the main outlet remains unchanged. However, the velocity contour result of the modification does not show a substantial difference as compared to the previous layout of third situation in the first modification as the area of zero velocity inside the factory is still small. Despite that, if the inlet of the factory is placed in the middle, all the bigger machine can cause the blockage of airflow from the inlet resulting in an unequal distribution of airflow throughout the factory because practically almost all the bigger and heavy-duty machine was located in the middle of the factory. As a result, the probability for the air flowing smoothly till the end of the factory is lower and will lead for the majority of dust remaining inside the factory during production hours.

Figure 4.15 illustrates the factory undergo the second situation of modification (B2) in which both location of inlet and main outlet are modified to be in the middle of the front and end of the factory respectively. The contour result show the zero-velocity area tend to increase in Station E as we can assume the station had completely become a stagnant area which may increasing the possibility for the dust to be accumulate inside the station and therefore increase the reading of particulate matter. Based on the result, the maximum velocity is estimated to be around 10.73m/s. The air velocity could be an important criterion for human thermal comfort because the increased air velocity will lead to a cooling effect. However, when the air velocity is too high, this may cause discomfort sensation. In general based on the observation, this type of modification is not a suitable and better option to been applied on the factory.

Last but not least, the modification has been done for the main outlet only where the main outlet is modified to be positioned in the middle at the end of factory while the location of the inlet is kept at same place which is in the corner of front part of the factory as shown in figure 4.16. This is considered to be the third situation of modification (B3). The result show an improvement as the zero-velocity area that presence at the lower corner of the factory at the very near too inlet as shown in both figure 4.14 and 4.15 are now absent. By comparing to second situation of modification (B2), velocity are slightly present in Station E. In comparison to the previous modifications the result show a reduce in the maximum velocity of the air flow.

Additionally, Hassan et al analysed two situations of inlet opening position to its side where the first cases shows the corner inlet openings to its side while the second cases shows the center inlet openings to its side. The result show the corner case of inlet opening can produce noticeable ventilation area inside a space more than the center case of inlet opening (Hassan et al., 2004). As comparison, the first case is similar to the third situation of modification (B3) while the second case is similar to the second situation of modification (B2) of this study. Therefore, the result obtain by Hassan can support the selection of B3 as the best improvement that can be done on the factory since the arrangement of the inlet and main outlet shown by third situation of modification (B3) provide a greater amount of ventilation area inside the factory which may lead to the smooth flow of air and ease process of eliminating dust form the factory.

Another studied on the effect of the relative location of the inlet and outlet openings in cross-ventilation on indoor air velocities by Abdin where includes of two cases as well. In the first cases, the inlet opening faces outlet opening while in the second case the inlet opening doesn’t face the outlet opening. The result demonstrates that the average indoor velocities in the first case were higher than these in the second case. For example, the indoor air velocity at the inlet and outlet openings was 90% and 40% of wind velocity, respectively. While for the second case, the indoor air velocity at the inlet and outlet openings was 60% and 20% of wind velocity, respectively (Abdin, 1982). By referring on all situation of modification proposed under the second modifications category, the third situation of modification (B3) satisfy the first case of Abdin's study where the inlet opening faces outlet opening thus it believe to have ideal average indoor velocities compared to others.

From the analysis, the third situation of modification B3 is selected as it give more improvement in the velocity analysis compared than others. The location of the inlet are better to be kept remain at the corner of the front factory while the main outlet should be moved to be in the center at the end of the factory so that the inlet opening faces the outlet opening for more amount of percentage of wind velocity at each opening, allowing for faster elimination of dust out from the factory especially during production hours.

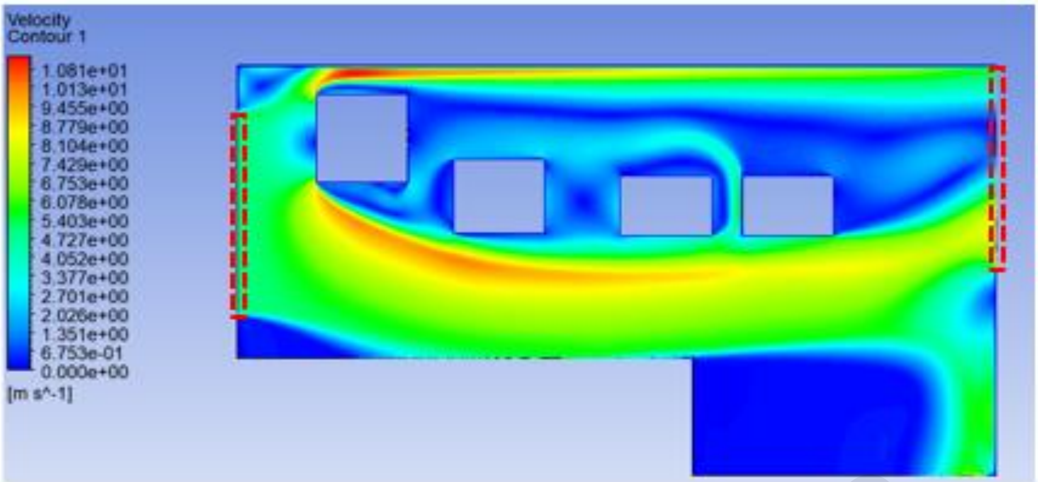


Figure 4.15: Inlet at the front middle of the factory, outlet at end corner of factory (B1)

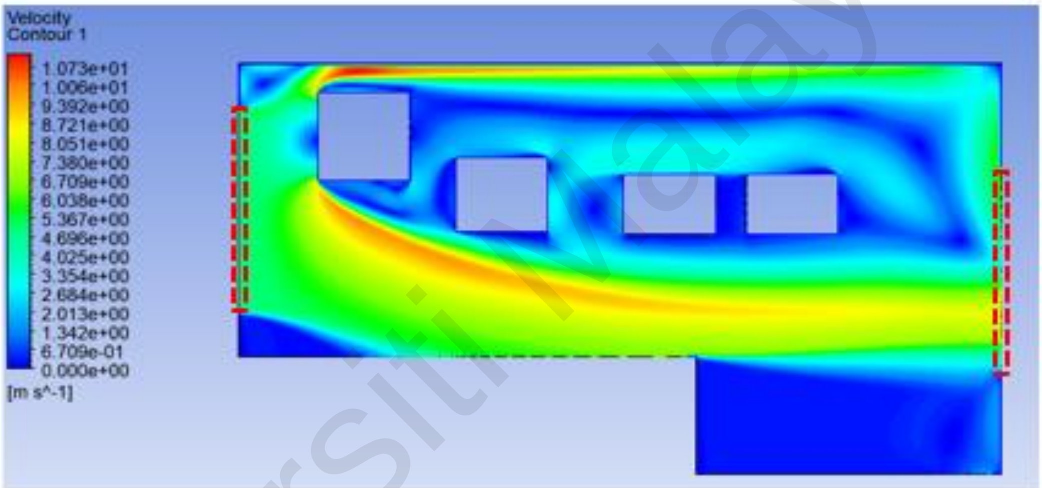


Figure 4.16: Inlet at the front middle of the factory, outlet at end middle of factory (B2)

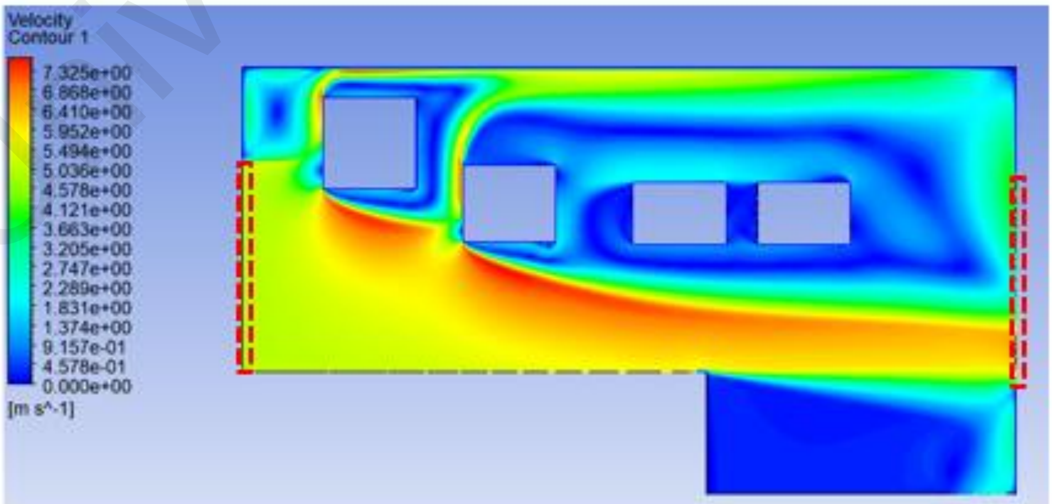


Figure 4.17: Inlet at the front corner of the factory, outlet at end middle of factory (B3)

C. Addition of Inlet in Station E

Inlet at the front corner of the factory, outlet at end middle of factory

As we refer on all the modification done, zero velocity area still dominating Station E as the blue contour color is covering almost all the space within the station. Thus, an addition of inlet is proposed in order to solve the problem. The station are modified to have an inlet at the adjacent wall of opening outlet as shown in figure 4.18.

The result show an improvement in the Station E as the uniform velocity result present in the station. Therefore, it is believed by adding an inlet at the station, the dust accumulation problem can be solved with the existence of the airflow within the station which help the dust produced during painting or spraying process to be eliminated out via the opening outlet exist more effectively with the assist of standing fan available inside the station. Furthermore according to Elwan et al, adding external wing walls at the openings of the windward side increases the airflow patterns inside indoor spaces (Elwan et al., 2018). Hence, from the findings it is proved that an addition of inlet within the station may help introducing velocity and improves air flow thus avoiding a zero-velocity area.

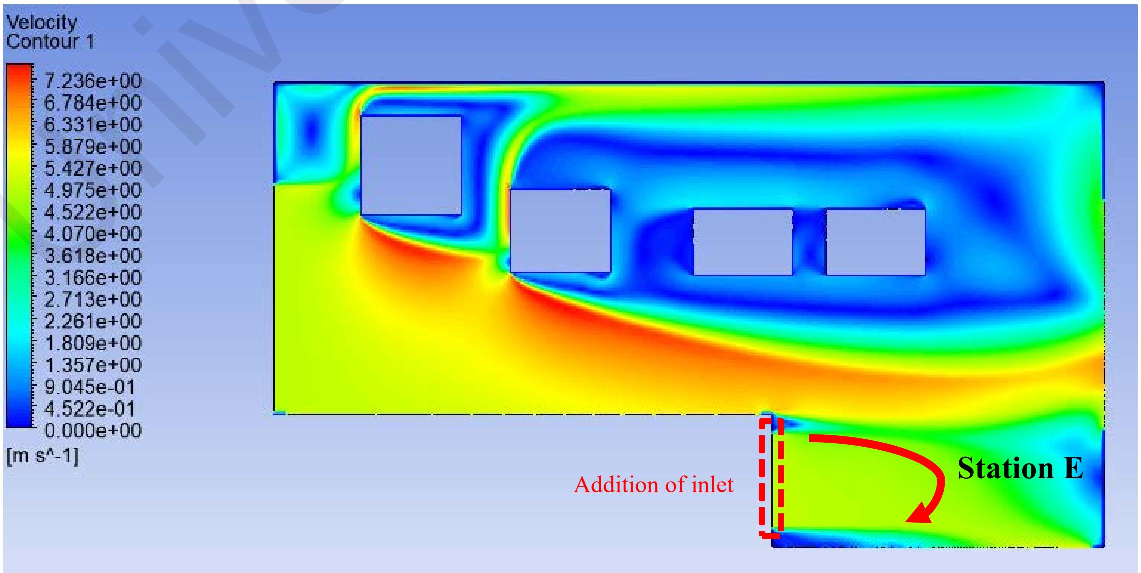


Figure 4.18: Addition of inlet at Station E

As overall, the result in identifying the best modification that could be implemented into the factory in the effort of minimize the stagnant area or zero velocity area that contribute to higher reading of particulate matter can be presented as follow the screening process shown in Figure 4.19 below.

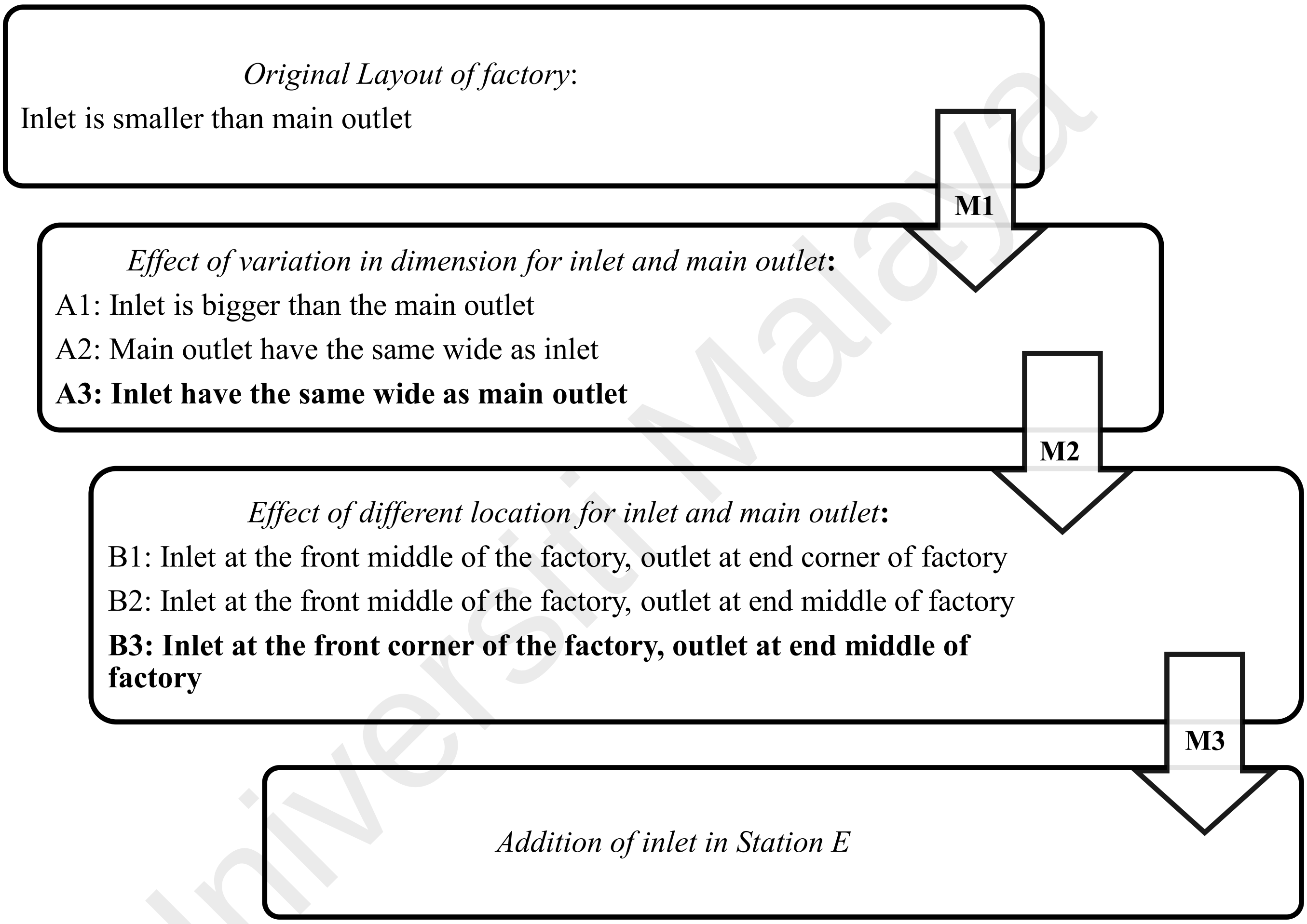


Figure 4.19: Screening process for the selection of best factory modification

Firstly, the original layout of factory which have smaller inlet and bigger main outlet is undergo first modification (*M1*) which is *effect of variation in dimension for inlet and main outlet.* After analysing the results, it is discovered that *improvement A3* gives the best result. By using the dimension and the size of the inlet and main outlet of *improvement A3,* then we further proceed to the second modification (*M2*) which is *effect* *of location for inlet and main outlet.* After analyses the result, it shows that *improvement B3* gives the best result. Unfortunately, Station E still did not show a better result after undergoing both *M1* and *M2* modification therefore we decided to undergo the third modification which is *addition of inlet in Station E.* By using the dimension of the inlet and main outlet of *improvement A3* as well as the location proposed in *improvement B3,* the factory model is then modified to have an addition of inlet location in Station E (painting and spraying) where it shows better result.

CHAPTER 5: CONCLUSION AND FUTURE WORK

Particulate matter are known to be the causes of respiratory hazards to workers in wood furniture industries. According to the permissible exposure limit (PEL) regulated by the Department of Occupational Safety and Health (DOSH), PM10 concentration exceeding 0.150mg/m^3 is unhealthy for workers and is hazardous if it is 0.180mg/m^{3}or more. Generally, from the result the highest and the lowest reading of PM concentration inside the factory are 0.354 mg/m^3 and 0.024 mg/m^3 respectively. Higher reading of particulate matter concentration inside the factory are likely to occur in the workstation that consist of big machine and perform heavy works such as CNC machine, wood planning machine and table sliding machine. During dust dispersion, dust separation occurred. Dust particles with larger diameters were more likely to settle under the action of inertial force. Smaller diameters of dust particle tended to become suspended and travel with the airstream.

The CFD modelling method was used to understand the features of air flow and dust distribution in a wood furniture industry. This study was conducted by CFD simulation to improve the velocity as well as the distribution of air flow within the factory since dust particle are depending on the flow of the air in order to be eliminated out through the arrangement of air distribution systems with different size and locations of the inlet and outlet opening in this study. According to this study, the ventilation arrangement and dust control measures are typical technical matters that can be optimized by conducting modeling studies and field tests. It was determined that a cleaner and safer working environment could be achieved through the proper integration of technology and management. This simulation could assist individuals in locating a more effective point to exert dust collection and help them create a better indoor environment.

Based on the simulation done, it was found that the size and positioning of inlet and outlet area have a significant impact on the air flow within the factory as it will influence the velocity of the air travelling from the inlet to the outlet. Largest air velocity happens if the inlet is small and the outlet is large. The total force is acting on a small area and forcing air through the opening at a high pressure. If the inlet opening is large, air velocity will be low but the volume of air passing in unit time will be higher. Consequently, an unbalanced system would be created. Hence, to have a smooth and uniform distribution flow of the air throughout the factory, the size of inlet and outlet opening need to have similar dimension. And it is suggested to have a wider inlet and outlet as shown by *modification A3* to lessen the airflow resistance that may exist if the opening for both inlet and outlet are too small since the nature of air flow always seeks the path of least resistance for it to travel smoothly inside the area. The selection of the location or position of the inlet and outlet opening also an important aspect to be considered because the present of obstructions within the building such as bigger machine will disrupt the air flow which causing it to loses its kinetic energy, each time it is diverted around an obstacle. Thus, it is recommended to have an arrangement of inlet and outlet as shown *modification B3* to have an ideal average indoor velocity. Last but not least, in order to reduce the zero-velocity area problem in Station E, an addition of inlet is required that may located at the adjacent wall of existing opening outlet of the area.

The current work on the flow of air and distribution of dust particle inside the factory is still in its early phases but it could lead to a better understanding and creation of more reliable and useful predictions of dust movement and distribution for wood furniture industry. Additional research are still needed, including particle models that take diameter distribution into account, air flow fields, various ventilation patterns, and appropriate heat and mass transfer processes. More effective ventilation method such as installation of exhaust fan and study their effectiveness in removing the dust also can be considered in the future work. In the future, the direct simulation to dust simulation could also be used to investigate the influence of more complex variables, such as number of indoor people. Computational capabilities and experimental measurement are and will remain intractable challenges in relation to the aforementioned topics, hence that improved models and new approaches to deal with dust behavior of air particle flow systems will be required.

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