

ANALYSIS OF ENGINEERING ECONOMICS OF THE NEW ERA COMPARED WITH THE CONVENTIONAL MATERIALS USED IN HVAC DUCT APPLICATION

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Received: March 23, 2024; Revised: May 24, 2024; Accepted: May 27, 2024

Abstract

Selecting suitable materials for air ductwork is essential to ensure efficient airflow distribution and reduce economic costs, as it directly impacts an air conditioning system's overall performance and functionality. The PVC-coated polyester canvas and foam materials have revolutionized the construction of air ductwork, offering numerous benefits and advantages over conventional materials. For instance, these materials have been successfully used in the construction of air ducts for large commercial buildings, resulting in significant energy savings and improved indoor air quality. Using these new-era materials has design flexibility, durability, energy efficiency, and cost-effectiveness. This research has provided a comprehensive analysis of the economic cost of the new era of air ductwork compared with conventional air ductwork in Thailand, and the thorough assessment of total service life costs has improved on the financial implications of adopting this new technology. The economic analysis of PID ducts reveals their cost-effective excellence compared to other investment types. The benefit-cost ratio of 4.73 and a payback period of 1.48 years show the financial advantages offered by PID ducts. With their affordability, efficiency, and simplicity, PID ducts emerge as the most attractive option for investors seeking long-term profitability and sustainability in construction projects.

Keywords: Air Ductwork; Air-Conditioning; Engineering Cost; Manufacturing Processes; New-Era Materials

Introduction

Nowadays, most humans do many activities inside buildings. Therefore, the indoor air environment must have suitable conditions to make the residents feel comfortable. Many engineers and researchers in air-conditioning systems have dedicated their efforts to studying various factors influencing

indoor air conditioning effectiveness. These factors include temperature, relative humidity, velocity, cleanliness, and noise. By understanding and controlling these variables, engineers can create optimal indoor environments that provide comfort and promote productivity for occupants.

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DOI: <https://doi.org/10.55766/sujst-2024-03-e03975>

Suranaree J. Sci. Technol. 31(3):010308(1-16)

The supply and distribution of conditioned air has two methods: the air-conditioning system used with split-type air-conditioning systems and the air-conditioning system with air ductwork commonly utilized with an Air Handling Unit (AHU) for larger areas such as open-plan offices, reception areas, conference rooms, or classrooms. An AHU paired with an air ductwork system is preferred when dealing with larger areas requiring greater airflow capacity. The AHU is a central hub that conditions and circulates the air throughout the space using a network of ducts. This method allows for better control over temperature and humidity levels in more extensive areas (Sribanurekha *et al.*, 2016).

Mechanical engineers prefer using the standards recommended by ASHRAE and SMACNA when designing conventional air ductwork due to their effectiveness in achieving efficient and durable systems. The galvanized steel sheet enhances these benefits, such as corrosion resistance and structural strength. Considering SMACNA guidelines ensures consistency in construction practices by following these industry-recognized standards and utilizing appropriate materials like galvanized steel sheets to ensure optimal performance and longevity of conventional air ductwork in HVAC systems.

Conventional air ducts encounter several problems. Firstly, the high airflow can lead to increased pressure drop and reduced air distribution efficiency (Bhuvad *et al.*, 2022), significantly impacting its performance. Moreover, energy losses occur due to poor insulation or inefficient design during the transmission of conditioned air through the ventilation system. All affect increased energy consumption and higher operating costs. Furthermore, the improper installation or maintenance of air ducts can exert excessive loads on building structures, potentially compromising their integrity and longevity. Consequently, substantial investments may be required to repair or reinforce these structures.

Considering the material and equipment cost of galvanized steel sheets, excluding value-added tax (VAT) and transportation cost in Bangkok, Thailand, the continuous compounding of the galvanized steel sheet price from 2.66 USD/m² in 2004 to 6.00 USD/m² in 2021 (Tanadecha and Khaothong, 2023). These fluctuating prices make the contractors unable to estimate the exact price for bidding. The calculated air ductwork cost commonly uses three methods: 1) Cost accounting method; this method gathers the cost of air ductwork information, then used to prepare a list of financial accounts to show the total expenditure of the project for cost management (Yekimov *et al.*, 2021). 2) Economic analysis method; this method gathers

the total cost of air ductwork, the lifetime, and the benefits information to evaluate the worthiness of the project (Christensen *et al.*, 2021) and 3) Cost analysis method in engineering terms; this method uses engineering principles to analyze the working process of air ductwork for reduce the cost but also remain the effectiveness. For the use of air ductwork in the air-conditioning system, engineers must consider related factors such as the ton of refrigeration (TR) of the air-conditioner, the building type, the air-conditioned area, the cost, and the project owner's need.

The air ductwork economic analysis consists of materials, equipment, operation, maintenance, and electrical energy costs, which are called economic costs, which are as essential as air distribution efficiency. In this way, Bouwman, (1982) designed air ductwork in the air-conditioning system and then analyzed three factors that affected the economic cost of air ductwork: air duct size, air-conditioned area, and heat loss, based on mathematical analyses and computer calculations. However, this method also needs to be revised. Therefore, Asiedu, (2002) created the cost model with the Kernel estimation technique and he asymptotic properties analysis to develop the Probability Distribution Functions (PDFs) in estimating the economic cost of air ductwork in air-conditioning systems; this method makes air duct cost estimation accurate, but it is difficult and complicated thus it is not suitable for use.

The economics cost analysis of air ducts is directly related to the air duct efficiency, especially the thermo-electric air duct system (TE-AD); it uses the potential energy of two different conductive materials to convert electrical power into thermal energy for the buildings that generate electricity from photovoltaic cells. Irshad *et al.* (2015) proposed the economic cost calculation method and air duct efficiency determination to evaluate thermoelectric air ductwork's economic and engineering worthiness. Dhief *et al.* (2016) developed methods of acoustic sources to reduce noise, giving air duct systems a suitable environment. In the case that the air duct has an air leak caused by the construction of air ductwork is not standardized or the deterioration due to lifetime (Ahn and Son, 2002), Abdelaziz *et al.* (2021) presented the principle of heat loss for analysis of the air leakage around the in-seam of air duct, that affects the economic cost and the air duct. Economic methods have a guideline for choosing materials to suit their needs and worthiness.

"Conventional" air ducts are known as metallic ductwork, produced from galvanized steel. Today, new materials that can be applied as air ducts to various user needs are called "new-era" air ducts.

These air ducts are known as non-metallic ductwork, including flexible or flex ducts and fabric ducts such as pre-insulate ducts (Krawczyk and Teleszewski, 2019), polyvinyl chloride (PVC) canvas (Craenenbroeck *et al.*, 2016), high-tension fabric (Jung *et al.*, 2020), and coating with polymer, include: polytetrafluoroethylene (PTFE) and ethylene tetrafluoroethylene (ETFE). All of the air ductworks have different engineering advantages and disadvantages. In practice, the economic analysis of air ductwork data has decided the owner of the project's benefits. It is used as a guideline for choosing materials to suit their needs and worthiness.

The COVID-19 pandemic tends to improve significantly, causing people to return to exercising in fitness centers, resulting in much new construction of fitness centers. The fitness center has electrical equipment and exercise equipment which use energy consumption, such as lights, fans, air-conditioners, treadmills, and weight training machines, which makes a lot of heat load; in addition, the exercise causes the service user to have a higher body temperature than average, it makes sensible and latent heat come out of the exercisers. Therefore, the air-conditioning system in the fitness centre must be suitable; the air distribution covers the entire area to create a good environment and make people feel comfortable.

This research studies the design of air ducts in air-conditioning systems for fitness centres with the static regain method and the economic analysis of the new era compared with conventional air ductwork.

Materials and Methods

Air ductwork

Air ductwork has four characteristics: 1) supply air ductwork distributes air throughout the air-conditioned area. 2) return air ductwork and bring the air in the air-conditioned area back to the air handling unit (AHU). 3) exhaust air ductwork to ventilate the exhaust air inside the air-conditioned area to the outside, and 4) fresh air ductwork, bringing the fresh air outside filling into the air-conditioning system (Cielo and Subiantoro, 2021). Air ductwork is commonly integrated with the AHU system, necessitating air circulation of suitable air quality, encompassing temperature, relative humidity, and air cleanliness, for human activities within the building (Kim *et al.* 2020).

Materials of air ductwork

The design Classified the air ductwork according to materials as follows:

1. Conventional air duct or Galvanized Steel Duct (GI Duct). It is made from galvanized steel sheet and insulated with Ethylene-Propylene Diene Rubber (EPDM), as shown in Figure 1(a), to maintain the temperature inside the air duct and reduce the noise from the vibration of the air duct due to airflow. To supply air, we must use the air grille diffuser.

2. Galvanized Steel Perforated Duct (GI Perforated Duct): This air duct is made from steel sheets and punches circular holes to supply air, as shown in Figure 1(b).

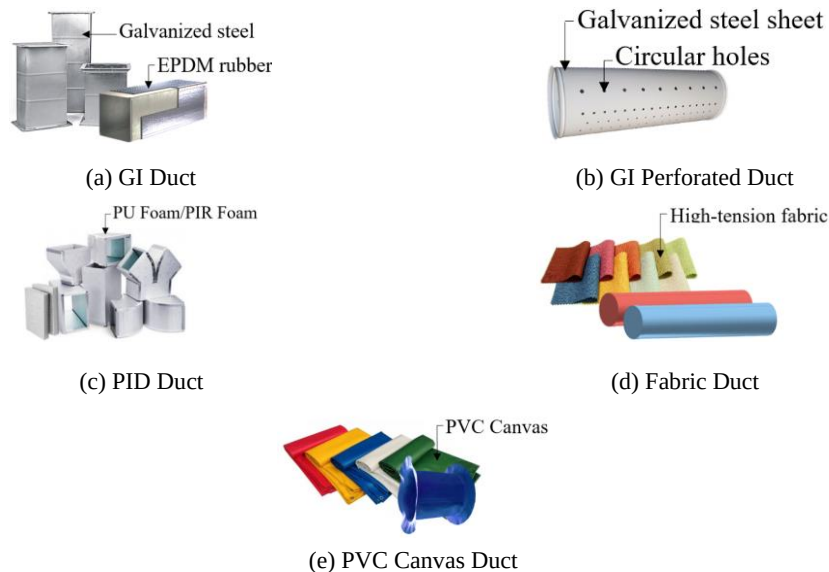


Figure 1. Air duct types

Now, let's explore the 'New era air duct': the Pre-Insulated Duct (PID Duct). This air duct, a testament to innovation and advancements in our industry, is made from polyurethane foam (PU Foam) or polyisocyanurate foam (PIR Foam) and covered on both sides with aluminum foil, as shown in Figure 1(c). Its outstanding feature is its thermal insulation properties (Sobhy *et al.*, 2021), making it a game-changer in air duct design. To supply air, an air grille diffuser is used.

3. Fabric Duct made from high-tension fabric and coated with a polymer, including polytetrafluoroethylene (PTFE) and ethylene tetrafluoroethylene (ETFE), as shown in Figure 1(d). It is lightweight and withstands tension forces without deformation, providing a durable and reliable solution for air ducts.

4. The PVC Coated Polyester Canvas Duct (PVC Canvas Duct). This material, made from polyvinylchloride (PVC) canvas, is a testament to the versatility and flexibility of air duct design. It can withstand tension forces and is coated with acrylic polyvinylidene fluoride (PVDF), as shown in Figure 1(e). The use of Knife coating technology allows for a variety of colours, making it a popular

choice for designers. The outstanding feature of the PVC Canvas Duct is its flexibility and high density, offering a range of design options. To supply air, you can use an air grille diffuser or distribute the air through the porous canvas, depending on the design of the designer. In addition to coating the canvas with PVC, some manufacturers may use other polymers such as polyurethane (PU), hydrophilic and hydrophobic.

Conventional air ducts are certified according to international standards recommended by ASHRAE and SMACNA. While the global standard for new-era air ducts is not, these ducts are usually referenced as class 1 ducts by Underwriters Laboratories (UL) 181 standard, (Reurings *et al.*, 2021) a requirement applying to materials in the fabrication of air ducts and air connector systems for product safety certification and compliance solutions, which was usually used by some manufacturers, especially in Asia. Thus, the designer must consider each air duct type by a certification standard in conjunction with specific material properties, engineering advantages, and disadvantages, as shown in Table 1.

Table 1. Engineering advantages and disadvantages of air duct

Material	Air duct	Advantages	Disadvantages
Conventional	GI Duct	1. long lifetime.	1. need the air grille diffuser.
		2. no need to coat it with color.	2. need to be insulated.
		3. can be used in buildings with and without ceilings.	3. high attack of airflow inside the air duct.
		4. resistant to all environments.	4. expensive.
		5. corrosion resistant.	5. fluctuated prices.
		6. can be installed outside the building.	6. heavyweight.
		7. old technology design engineers have proficient in design.	7. difficult to installation.
		8. have international standards.	8. a lot of steam condensation.
	GI Perforated Duct	9. installation process produces zinc poisoning.	9. installation process produces zinc poisoning.
		10. difficult to maintenance.	10. difficult to maintenance.
		1. no need for the air grille diffuser.	1. no corrosion resistant.
		2. easy to choose the air distribution position.	2. heavyweight.
		3. distribution of the air covers the entire area.	3. noise.
		4. resistant to all environments.	4. can be used in buildings without ceilings.
New Era	PID Duct	5. low air leakage.	5. expensive.
		6. old technology design engineers have proficient in design.	6. difficult to installation
		7. have international standards.	7. installation process produces zinc poisoning.
		1. can maintain the air quality.	8. complex to maintenance.
		2. no need to be insulated.	1. need the air grille diffuser.
		3. lightweight.	2. burning may produce poison such as CO, CO ₂ , NOx, etc.
		4. quiet and sound absorbing from air delivery.	3. have air leakage.
		5. easy to installation.	4. not suitable for use outside the building.
		6. save energy consumption.	5. no relevant legislation.
	Fabric Duct	7. have a beautiful air ductwork pathway.	6. complex maintenance.
		8. the design can use the same principle as GI Duct.	
		9. have UL 181 standard.	
		1. no need to be insulated.	1. in high airflow, the air velocity distribution inside the air duct is uneven.
		2. low airflow, air delivery does not cause noise.	2. high flexibility.
		3. air supply is evenly distributed.	3. can be used in buildings without ceilings.
		4. easy to installation.	4. not resistant to jolt.
		5. can be designed to reach the blind corner of the area.	5. not suitable for use outside the building.
		6. save energy consumption.	6. no relevant legislation.
		7. lightweight.	7. the design requires specific information from the manufacturer; ordinary engineers cannot design.
		8. variety of colors suitable for architectural decoration.	8. high pressure drop and affect to the operation cost and efficiency estimation.
		9. maintenance easily, washing with a standard washing machine.	
		10. have UL 181 standard.	

Table 1. Engineering advantages and disadvantages of air duct

Material	Air duct	Advantages	Disadvantages
New Era	PVC Canvas Duct	- no need to be insulated. - can choose to use or not use the air grille diffuser. - airflow through the air duct is cleanliness. - resistant to sunlight and moisture. - have a smooth surface. - withstand tension forces. - easy to installation. - save energy consumption. - cheap. - the design can use the same principle as GI Duct. - variety of colors suitable for architectural decoration. - maintenance easily, wiping with water or cleaning solution. - have UL 181 standard.	- high flexibility. - can be used in buildings without ceilings. - low strength. - low fire resistance rate compared to other types of air duct. - difficult to maintain the temperature. - the deterioration makes the canvas may become dry and hard, causing cracks and leaks easily. - no relevant legislation. - no international standard. - high-pressure drop affects the operation cost and efficiency estimation.

Table 2. The information related to the air-conditioning design in each fitness centre room.

Room	Area (m ²)	Heat source	Heat load (kW)	Cooling load (kW)
Yoga room	45.12	- people during exercise. - exercise machine, such as a treadmill, recumbent bike, etc. - light bulbs. - solar heat gain through glass.	30.57	35.16
Café room	101.68	- people during a normal activity. - kitchen appliances, such as refrigerators, stoves, microwaves etc. - light bulbs.	22.93	26.37
Retail room	153.60	- people during a normal activity. - light bulbs. - other electrical appliances	53.50	61.53

Air ductwork design

The air ductwork design process must consider; 1) Building structure and architectural style, viz: the ceiling structure, the distance between air ductwork and ceiling of the building, location, and weight of air ductwork, and 2) Mechanical engineering work, viz: air-conditioned area, a ton of refrigeration (TR) of air-conditioner, the velocity of airflow, pressure drop, air leakage, air ductwork pathway, noise and heat transfer of air ductwork. The ASHRAE Technical Committee 5.2 in 2021 requires the air ducts to introduce the air ductwork design methods: the equal friction method, the velocity reduction method, and the constant velocity method, but the static regain method is accessible to the supply air ductwork design for the AHU system, especially in the complicated pathway and high-velocity airflow. The main principle of this method is to set the static pressure maintained the same before each terminal or branch and design the air duct size to reduce the pressure, assuming as the path of each air duct has a balance of static pressure, the increase in static pressure is precisely equal to the decrease in velocity pressure and the assuming total pressure remains constant. The design of air ductwork is to supply and distribute fresh air to the roof structure of the building. The distance between the air ductwork and the ceiling location of the obstruction and weight is considered because the heavy air ductwork may affect the load on the roof and building structure (Dai *et al.*, 2022).

This paper studies air ductwork design in the air-conditioning system for a fitness centre in Bangkok, Thailand. (GPS MCJX+4QP, Rama II Soi 44, Chom Thong, Bangkok). The fitness centre has an air-conditioned area size of 300.40 m²; the air-conditioning system needs a cooling load size of 123.06 kW; it is divided into three rooms: 1) Yoga room, 2) Café room and 3) Retail room, which shows the information related to the air-conditioning design in Table 2.

This paper studies the economic analysis of the investment, operation, maintenance, and electrical energy costs of a split-type air conditioner in a conventional air-conditioning system (no air ductwork), as shown in Figure 2. Then, using the static regain method, the GI Duct is designed to have a cooling capacity equal to that of the split-type air conditioner for the air-conditioned area, as shown in Figure 3. The air ductwork can control the climate of the fitness centre environment.

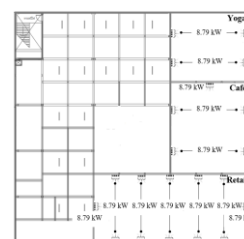
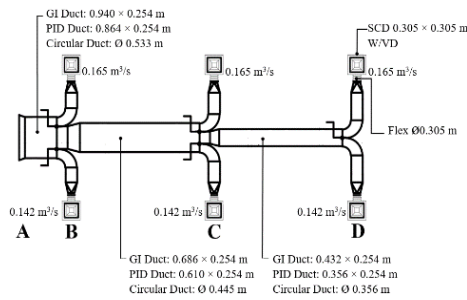
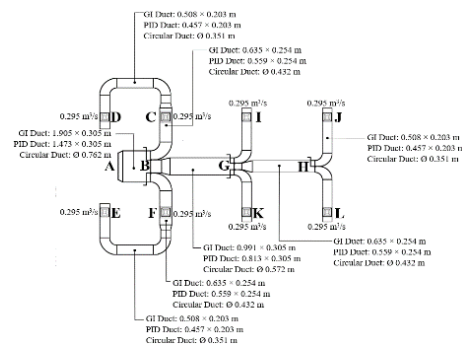


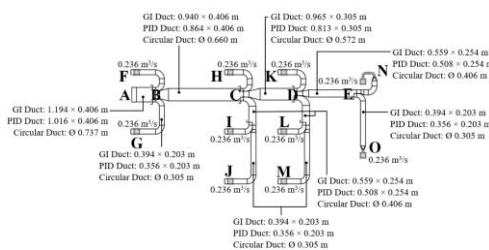
Figure 2. The split-type air conditioner in a conventional air-conditioning system (no air ductwork) for the fitness center



(a) Yoga room



(b) Café room



(c) Retail room

Figure 3. The results of air duct design for the fitness center

In the new era of material design, engineers consider air ductwork made from different materials, which has various advantages and disadvantages in engineering and the worthiness of investment and air duct efficiency to the optimizing needs of the project's owner and people who come to use the fitness centre service. This paper studies and designs the air ductwork, a GI Duct compared with a GI Perforated Duct, PID Duct, Fabric Duct, and PVC Canvas Duct by the static regain method, which analyzed the pressure drop by Colebrook's equation, calculated by equation (1) to equation (3)-the surface roughness (ϵ) of the air duct, as shown in Table 3. For the circular air duct design as follows: GI Perforated Duct, Fabric Duct, and PVC Canvas Duct with the static regain method must be calculated as the equivalent round duct, calculated by equation (4), to determine the air duct size that is minor, equal, and diffuses the air with quality similar the square duct. Due to the air ductwork design that has the branch

duct, it is necessary to consider the minor losses. Calculated by equation (5).

$$\frac{1}{\sqrt{f}} = -2 \log \left(\frac{\varepsilon}{3.7 D_h} + \frac{2.51}{\text{Re} \sqrt{f}} \right) \quad (1)$$

$$\text{Re} = 66.4 D_h V ; \text{ For standard air} \quad (2)$$

$$D_h = 4A/P \quad (3)$$

$$D_e = \frac{1.30(ab)^{0.625}}{(a+b)^{0.250}} \quad (4)$$

$$\Delta p_j = C_b p_v \quad (5)$$

Where f is friction factor; D_h is the hydraulic diameter of the duct cross-section (m); V is kinematic viscosity (m^2/s); A is air duct cross-sectional area (m^2); P is the circumference of the air duct (m); ε is surface roughness (m); Re is reynolds number; D_e is equivalent to round duct diameter (m); a is air duct cross-sectional area width (m); b is air duct cross-sectional area length (m); Δp_j is total pressure loss (Pa); C_b is the loss coefficient for the branch flow paths and p_v is velocity pressure (Pa).

Table 3. Surface roughness of air duct

Air duct	Surface roughness (mm)
GI Duct	0.500
GI Perforated Duct	0.500
PID Duct	0.150
Fabric Duct	0.038
PVC Canvas Duct	0.040

The air duct design with the static regain method determines the path of each air duct with a balance of static pressure. It must divide the air duct into sections, according to the branch and the supply air grille diffuser, due to the airflow delivered through the part of the air duct and the supply air grille diffuser decreasing the velocity and kinetic pressure of airflow in the following path, resulting in, the static pressure increase. The air ductwork sizing is calculated by equation (1) through equation (5), as shown in Table 4.

For the design of the circular cross-section with the static regain method, the design results show in terms of equivalent round duct, due to the circular duct use a lot of material and equipment, which means it has a high cost. Therefore, the air duct design must be small, equal, and efficient for distributing the air. The three types of circular ducts are GI Perforate Duct, Fabric Duct, and PVC Canvas Duct.

Table 4. The air ductwork design results

Air ductworks		GI Duct (m)	PID Duct (m)	The three types of circular duct* (m)
Yoga room	part A-B	0.940×0.254	0.864×0.254	$\varnothing 0.533$
	part B-C	0.686×0.254	0.610×0.254	$\varnothing 0.445$
	part C-D	0.432×0.254	0.356×0.254	$\varnothing 0.356$
Café room	part A-B	1.905×0.305	1.473×0.305	$\varnothing 0.762$
	part B-C	0.635×0.254	0.559×0.254	$\varnothing 0.432$
	part B-E	0.635×0.254	0.559×0.254	$\varnothing 0.432$
	part C-D	0.508×0.203	0.457×0.203	$\varnothing 0.351$
	part E-F	0.508×0.203	0.457×0.203	$\varnothing 0.351$
	part B-G	0.991×0.305	0.813×0.305	$\varnothing 0.572$
	part G-H	0.635×0.254	0.559×0.254	$\varnothing 0.432$
	part G-I	0.508×0.203	0.457×0.203	$\varnothing 0.351$
	part G-K	0.508×0.203	0.457×0.203	$\varnothing 0.351$
	part H-J	0.508×0.203	0.457×0.203	$\varnothing 0.351$
	part H-L	0.508×0.203	0.457×0.203	$\varnothing 0.351$
Retail room	part A-B	1.194×0.406	1.016×0.406	$\varnothing 0.737$
	part B-C	0.940×0.406	0.864×0.406	$\varnothing 0.660$
	part C-D	0.965×0.305	0.813×0.305	$\varnothing 0.572$
	part D-E	0.559×0.254	0.508×0.254	$\varnothing 0.406$
	part B-F	0.394×0.203	0.356×0.203	$\varnothing 0.305$
	part B-G	0.394×0.203	0.356×0.203	$\varnothing 0.305$
	part C-H	0.394×0.203	0.356×0.203	$\varnothing 0.305$
	part D-K	0.394×0.203	0.356×0.203	$\varnothing 0.305$
	part C-I	0.559×0.254	0.508×0.254	$\varnothing 0.406$
	part D-L	0.559×0.254	0.508×0.254	$\varnothing 0.406$
	part I-J	0.394×0.203	0.356×0.203	$\varnothing 0.305$
	part L-M	0.394×0.203	0.356×0.203	$\varnothing 0.305$
	part E-N	0.394×0.203	0.356×0.203	$\varnothing 0.305$
	part E-O	0.394×0.203	0.356×0.203	$\varnothing 0.305$

*The three types of circular ducts are GI Perforate Duct, Fabric Duct, and PVC Canvas Duct.

Air ductwork quantity

In the economic analysis of air ductwork systems, an estimating engineer used the quantity take-off method to calculate quantities of materials required for a bill of material in an air ductwork construction, with the following steps:

1. Study the air ductwork details and decide to calculate the quantity of air ductwork material by floors and rooms of the building.
2. Study the types of equipment used in the air ductwork.
3. Classify the types of Air Handling Units (AHU) connected to each set of air ductwork and estimate the quantity.
4. Classify the types of air grills used in each set of air ductwork and estimate the quantity.
5. Divide the air ductwork into sections and classify an air duct by the types, such as straight, curved, and reducing; calculate the material area and count the number of installation equipment.
6. Study the material equipment and installation costs of air ductwork.
7. Calculate the total cost and compare it to the engineering advantages and disadvantages of each air ductwork type.
8. Estimate the preliminary cost of the air ductwork construction before the actual building to let the owner know the benefits of the project's worthiness.

All the take-off processes aid engineers in planning budgets and reducing project costs, leading to an agreement between the project's owner and the building contract company. The air ductwork type is similar and made from different materials. There are differences in the quantities area and the number of material equipment because the production and installation process of each type is different, as detailed below:

1. The GI Duct is formed by bending galvanized steel sheets into the size and shape of the air duct as required. In the bending process causes, the outer surface of the galvanized steel sheet will be pulled, resulting in the elongation of the steel sheet, called the bending Poisson's effect, and the inner surface of the galvanized steel sheet will be pressed, resulting in a bend radius. Therefore, in the method of estimating, the bending part q/area is about 30 percent of the galvanized steel sheet material area (Tipalin *et al.*, 2020). Furthermore, the GI ductwork design is imperative to the thickness suitable to the SMACNA standards, which recommend about 0.45-1.2 mm. According to the market standards in Thailand, the thickness determination of galvanized steel sheets is specified as a thickness number, as shown in Table 5.

2. GI Perforated Duct is formed by drilling holes on galvanized steel sheets to a suitable size for distributing the air by laser drilling. The proper size

Table 5. Galvanized steel sheet thickness number available in the Thailand market

Thickness number	Thickness (mm)
#26	0.45
#24	0.55
#22	0.70
#20	0.90
#18	1.20

of spots depends on the air duct diameter, air velocity outlet, characteristics of air ductwork, and implementation (Tiryakioglu, 2022). That means these air duct types do not require the air grill to distribute the air (Thao *et al.*, 2021); quantity take-off contemplates the thickness suitable for use, like the GI Duct (Asati *et al.*, 2022).

3. PID Duct is formed by connecting each pre-insulated sheet using the Z-Lock technique, a technology for connecting pre-insulated sheet panels with a smooth seam along the entire length, an uncomplicated course to reduce air leakage over the seam. The thickness suitable for air ductwork in conditioning systems is about 20 to 50 mm. Quantity take-off does not need the reserved area for bending where the material used is less than the GI Duct.

4. Fabric Duct is formed by sewing the high-tension fabric. The fabric is coated with a polymer to withstand tension forces without deformation and increase fire resistance. Furthermore, it tests fabric strength and failing load when used under high air pressure with simulation and experimental methods. A characteristic of a Fabric Duct is a circular duct; the fabric is porous and does not require the air grill to distribute the air. The design of the Fabric Duct must consider the distribution of airflow to be consistent and must design the direction of air ductwork to be suitable. These air duct installation processes use the fabric together with duct hangers to hang the air duct to the ceiling of the building. The suitable thickness of the Fabric Duct is 0.08 to 0.18 mm.

5. The PVC canvas duct is formed by weaving the polyester fibre-coated cross vertically (warp) and horizontally (weft) to make the canvas withstand the tension force. This canvas is coated with polymer by layers such as polyvinylchloride (PVC), acrylic, and ultraviolet; UV makes the canvas resistant to sunlight and moisture. In form, the hot air or induction welding method is commonly used, a technology for fusing the canvas (Santos *et al.*, 2021). The decision to use or not use the air grill depends on the user's characteristics and the project's owner's needs. In PVC Canvas Duct quantity, take-off should consider the air duct usage and thickness to suit the air-conditioning system. The standard available thickness of air ducts in the

Thailand market is 0.08 to 0.18 mm, like the Fabric Duct.

Results and discussion

Total cost analysis for air ductwork in the air-conditioning system

The total cost difference in air duct type comes from the different designs of air ductwork, material equipment, installation process, and maintenance. The method of all air duct design considers the principle shown in equation (6): Calculating the total cost of air ductwork can analyze the budget used, compare the total cost throughout the service life, and find the type of air ductwork worthwhile, including the considering the advantages and disadvantages in engineering and the project's owner's needs.

$$C_{Total} = C_{Investment} + C_{Maintenance} + C_{Energy} + C_{Operating} \quad (6)$$

When $C_{Investment}$ is investment cost, which is the cost of materials, and equipment for air ductwork that occurs before and during construction (USD; \$); $C_{Maintenance}$ is the maintenance cost of air ductwork (USD/year); C_{Energy} is electrical energy cost throughout the service life of air ductwork (USD/year); $C_{Operating}$ is the operating cost of air ductwork (USD; \$).

1. Investment cost ($C_{Investment}$) of air ductwork: This research considered the price and standard sizes of air ductwork available in the Bangkok, Thailand, market because the fitness center is in Bangkok. The exchange rate of a currency between the Baht (Bath; ฿) and the US dollar (USD; \$) as of 7 November 2022 equals 37.40 Bath per 1 US (<https://www.bot.or.th/th/home.html>, 2022) the details of materials and equipment prices are shown in Table 6.

2. Maintenance cost ($C_{Maintenance}$) of air ductwork: The benefits of air ductwork maintenance are safety and increased efficiency system. The type of air ductwork has different maintenance procedures: PID, GI, and GI Perforated ducts use a robot to clean the inside. Fabric Duct can be removed and washed by a usual washing machine. Moreover, PVC Canvas Ducts can be wiped. Generally, the Department of Energy Development and Promotion Ministry of Energy Thailand recommended that it be checked every six months. The maintenance engineer will prepare a schedule for inspection and maintenance according

to the usage characteristics, environment, and air-conditioned area. The optimal air ductwork type system to supply air into an air-conditioned area is cost-effective. Usually, the maintenance cost per time is determined by the size, area, and location of the air ductwork, as shown in Table 7.

Assume that the lifetime of air ductwork is ten years due to all types of air ductwork working effectively with no repairs. The strength of air ductwork, equipment replacement, efficiency, etc., affect the maintenance cost estimation. Figure 4 shows the result of the maintenance cost analysis.

Table 6. The details of materials, equipment price of five types of air ductwork

Air duct type	Materials equipment	Size	Price per unit (USD; \$)	
GI Perforated Duct	90° Elbow	Ø 355	21.31	
		Ø 300	17.34	
	45° Elbow	Ø 450	23.35	
		Ø 400	17.62	
		Ø 355	14.07	
		Ø 300	12.34	
		Cap	Ø 630	24.53
	Ø 355		6.93	
	Ø 300		4.83	
Total investment cost of air ductwork			22,484.39	
PID Duct	Pre-insulated sheet panel	1.2 × 3.95	m ²	38.62
	Tiger connector	-	-	0.31
	PVC Flange	4	m	4.01
	U Flange	4	m	4.01
	Bayonet	4	m	2.72
	Plate angle	-	-	0.20
	Cover angle	-	-	0.34
	Square air grille diffuser	0.3048 × 0.3048	m	14.28
		0.4064 × 0.4064	m	25.00
Total investment cost of air ductwork			13,566.54	
Fabric Duct	Fabric	Thickness 0.10	mm	6.68
		Thickness 0.12	mm	8.02
		Thickness 0.14	mm	9.36
		Thickness 0.16	mm	10.70
		Thickness 0.18	mm	12.03
	Hanger	1	m	66.84
Total investment cost of air ductwork			20,622.67	
PVC Canvas Duct	PVC Canvas	2.5 × 1	m ²	13.05
	Hanger	1	m	66.84
	Circular air grille diffuser	ø304.8	mm	21.39
		ø406.4	mm	34.65
Total investment cost of air ductwork			21,307.32	
GI Duct	Thickness number #18	1.2 × 2.4	m ²	43.98
	Thickness number #20	1.2 × 2.4	m ²	32.01
	Thickness number #22	1.2 × 2.4	m ²	25.01
	Thickness number #24	1.2 × 2.4	m ²	19.77
	Thickness number #26	1.2 × 2.4	m ²	16.84
	Ethylene-Propylene Diene Rubber (EPDM) insulation	0.914 × 1.219	m ²	16.56
	Square air grille diffuser	0.3048 × 0.3048	m	14.28
Total investment cost of air ductwork			16,260.42	
GI Perforated Duct	Straight air duct	Ø 710	mm	120.17
		Ø 630	mm	104.59
		Ø 560	mm	48.59
		Ø 450	mm	62.89
		Ø 400	mm	29.08
		Ø 355	mm	49.71
		Ø 300	mm	42.69
		Ø 450/ Ø 355	mm	57.91
	90° Reducing Tee	Ø 450/ Ø 355	mm	57.91
	Y Reducing Tee	Ø 630/ Ø 300	mm	175.13
		Ø 400/ Ø 300	mm	33.62
	45° Reducing cross	Ø 710/ Ø 450	mm	523.54
		Ø 710/ Ø 300	mm	523.54
		Ø 630/ Ø 400	mm	209.55
		Ø 560/ Ø 355	mm	187.45
	Reducing socket	Ø 710/ Ø 630	mm	52.18
		Ø 710/ Ø 560	mm	68.95
		Ø 630/ Ø 560	mm	39.82
		Ø 630/ Ø 300	mm	36.46
		Ø 560/ Ø 450	mm	31.07
Ø 450/ Ø 355		mm	20.33	

Table 7. The price of air ductwork maintenance in the air-conditioning system

Air ductwork	Maintenance method	Maintenance cost per time
Conventional air-conditioning system (no air ductwork)	Air-conditioner cleaning	16.04 – 21.39 \$/ device
GI Duct	Cleaning robot	0.20 – 0.39 \$/m ²
GI Perforated Duct	Cleaning robot	0.20 – 0.39 \$/ m ²
PID Duct	Cleaning robot	0.20 – 0.39 \$/ m ²
Fabric Duct	Washing and installing again	0.28 – 0.32 \$/ m ²
PVC Canvas Duct	Wipe for clean	0.12 – 0.16 \$/ m ²

The maintenance cost per year for Fabric Ducts is the most expensive due to the maintenance process involving the cost of dismantling, washing, and reinstalling. The use of an air ductwork system to supply the air into the air-conditioned area is economical; the maintenance cost is less than the conventional air-conditioning system (no air ductwork) because the maintenance process of all of the air ductwork is easy, and maintenance cost per time considering by size and area of air ductwork is cheaper than the air-conditioner cleaning. The results show that the Fabric Duct maintenance cost per year is the most expensive because the maintenance process involves the cost of dismantling, washing, and installing again.

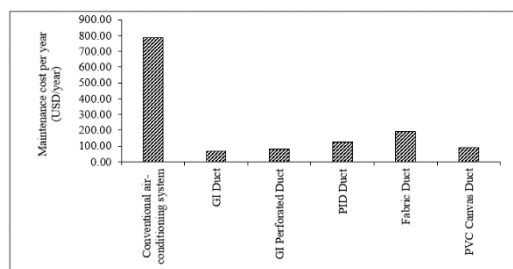


Figure 4. Maintenance cost per year of air ductwork in an air-conditioning system

3. Electrical energy cost (C_{Energy}) of air ductwork: An inspection of the various systems' electrical energy consumption in buildings found that the air-conditioning system is the most consumed, accounting for 53% of total electrical energy used, especially the high electrical energy cost in terms of business. Therefore, using the air-conditioning system should consider the electrical energy cost. Each type of air duct used with the air-conditioning system has inequitable energy consumption; thus, the air duct material has different heat exchange properties (Nejadpak and Rao, 2020), as shown in Table 8.

Table 8. Thermal conductivity of air duct

Air duct	Thermal conductivity (W/m-K)
GI Duct	52.00
Insulation	0.038
GI Perforated Duct	0.270
PID Duct	0.024
Fabric Duct	0.050
PVC Canvas Duct	0.048

Considering the electrical energy cost of air duct from the rate of air duct heat transfer and analyzing the results in terms of the electrical energy cost per year, when determining the electrical energy consumption cost from the Metropolitan

Electricity Authority in 2022, it is equal to 0.099 \$/kW (Tanadecha and Khaothong, 2023), as shown in Figure 5.

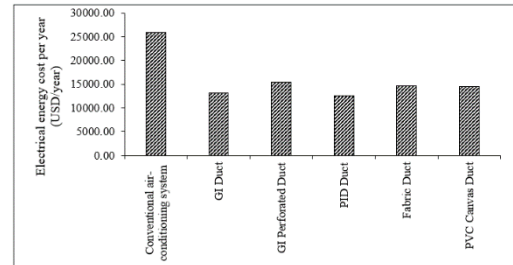


Figure 5. Electrical energy cost per year of air ductwork in air-conditioning system

Using air ductwork in the air conditioning system to supply the air into the air-conditioned area has an electrical energy cost per year less than the conventional air-conditioning system (no air ductwork), which requires many air conditioners to distribute the air into the entire air-conditioned area. The results show that the PVC Canvas Duct electrical energy cost per year is the most expensive because it has high thermal conductivity and uses high energy consumption to maintain the temperature inside the air duct.

4. Construction cost of air ductwork:

The calculation for estimating the construction cost of air ductwork has divided: a yoga room, a Café room, and a Retail room are investment cost ($C_{Investment}$); on account of air ductwork construction, the designer must calculate the number of material equipment used to supply the air, and the operating cost ($C_{Operating}$). Figure 6 shows the quantity of material used for five types of air ductwork.

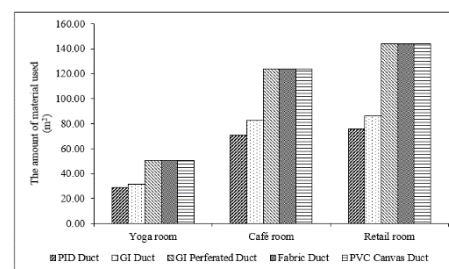


Figure 6. Comparison results of the quantity of material used for air ductwork in each room of the fitness center

The analysis showed the quantity of material used for air ductwork, the cost of materials and equipment, and the cost of installation for the fitness center, which consists of a Yoga room; this room has two air ducts line, and each air duct line operates in tandem with the features 17.58 kW air handling

system. Café and Retail room have air ductwork used in tandem with 43.96 kW air handling systems according to the cooling load size as shown in Figure 2.; analyzed the quantity of material, together with the air handling system, that is suitable for the air-conditioned area in terms of square meters per kilowatt (m^2/kW) and analyzed the construction cost of air ductwork shown in Figure 7. The results show that the PID Duct, made from Polyisocyanurate foam (PIR), is square. This air duct has the lowest quantity of material used, calculated for 1.39 m^2/kW , because it used Z-Lock technology for connecting pre-insulated sheet panels with a smooth seam, eliminating the need for space for bending the board. The construction cost of air ductwork depends on air duct size and length; because the large and long air duct used a lot of materials and equipment, the PID Duct investment cost is more expensive than the GI Duct, calculated for 13%, more than the Fabric Duct, calculated for 33% and more than the PVC Canvas Duct, calculated for 29%. Still, the PID Duct operating cost is cheap because it is lightweight and easy to cut and assemble.

The GI Duct is made from a galvanized steel sheet, characterized as a square duct. The material used equals 1.58 m^2/kW , whereas a portion of the total material, known as the ‘bending spare’, is used for 30% of the total material. The GI Duct construction cost depends on the air duct design. These air ducts use the air grille diffuser and are insulated with Ethylene-Propylene Diene Rubber (EPDM) to maintain the temperature inside the air duct. The design must have a thickness to suit the air duct size and air flow velocity; the high solidness of the GI Duct has a high investment cost and operating cost. However, the designer’s expertise directly affects the quantity of material used in the GI Duct.

The GI Perforated Duct is made from a steel sheet and is characterized as a circular duct resulting in the air duct design; the assembling and installing the air duct requires a large quantity of material, calculated for 2.51 m^2/kW . The circular duct has various sizes as designed; therefore, it is easy to connect, which makes the GI Perforated Duct quantity of material used higher than the GI Duct, which is a square duct formed with bending to reduce air leak. Evaluating the construction cost of the GI Perforated Duct depends on the design similar to the GI Duct, so it must choose the thickness to suit the air duct size and airflow velocity. However, the GI Perforated Duct design should consider the suitable size, numbers, and position of holes that punch for supply air. Because the punching process with laser drilling technology is expensive, these air ducts require high investment and operating costs. The construction cost of the GI

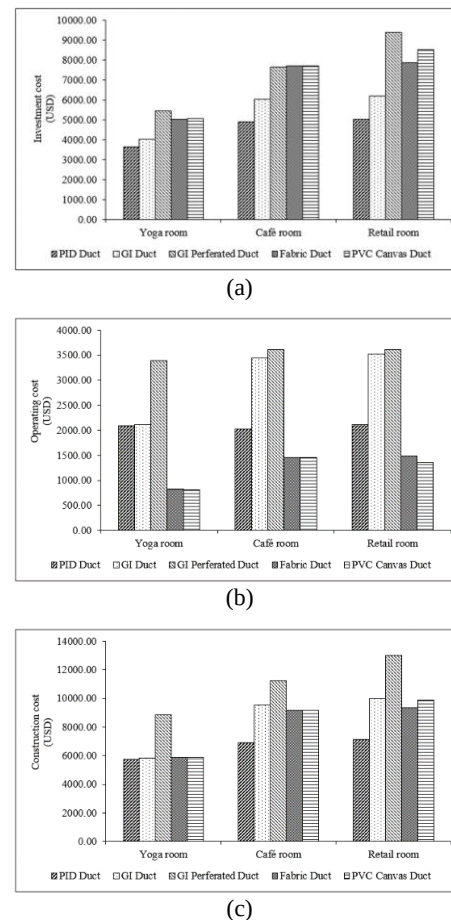


Figure 7. (a) Comparison results of the investment cost. (b) Comparison results of the operating cost. (c) Comparison results of the construction cost of five types of air ductwork for each room of the fitness centre

Perforated Duct depends on the design; for example, In the cause of the designer chooses the 90° elbow, it will be more expensive than the 45° elbow, etc., the designer must have the expertise to design the air duct. The results of estimating the construction cost of the GI Perforated Duct are higher than the GI Duct, which is calculated at 5.54%.

The Fabric duct and the PVC Canvas Duct are made from polymer fibre materials and characterized as circular ducts like the GI Perforated Duct; therefore, they are designed to have the same quantity of material used as the GI Perforated Duct, calculated for 2.51 m^2/kW . The Fabric duct and the PVC Canvas Duct have an area of crease, the seam in the stitching, the hangers for installation, and the materials and equipment costs are similar then; they have almost equal construction costs, but the PVC Canvas Duct used the air grille diffuser, resulting in the construction cost of the PVC Canvas Duct is higher than the Fabric Duct, calculated for 2.22%.

The GI Perforated Duct, the Fabric Duct, and the PVC Canvas Duct have the most material used for air ductwork as equal; these air ducts are characterized as circular ducts. Following the GI Duct indicated as a square duct, the calculation must reserve the material used for the bending. The PID Duct, characterized as a square duct, is the less quantity of material used in forming assembly that connects to pre-insulated sheet panels with a smooth seam and no need to reserve the area. The designed analysis of the GI Perforated Duct and the Fabric Ducts must punch holes to supply the air through all altitudes. These air ducts can distribute the air into the air-conditioned area better than using the air grille to deliver the air at the design position. The quantity of material used in the calculation should consider the punching hole area. For the results of the construction cost of five types of air ductwork found that the GI Perforated Duct has the highest construction cost and higher than the conventional air-conditioning system (no air ductwork), calculated for 12.89% because it has the most increased investment cost compared to others and these air ducts are large and heavy, that makes wasting space in transportation and difficult to installation. They are followed by the GI, PVC Canvas, and Fabric Duct, respectively. Furthermore, the PID Duct has the lowest construction cost, showing that these air ducts have lightweight foam, which makes it easy to transport, reduces surface, and is easily split and assembled to install, resulting in low operating costs.

Instead of the conventional air ductwork, the air-conditioning system (no air ductwork) can distribute the air throughout the air-conditioned area. Comparing the different construction costs for the three rooms suitable for using the air-conditioning system, we found that the GI Perforated Duct in all rooms has the highest construction cost, followed by the PVC Canvas Duct and the Fabric Ducts, respectively. The PID Duct in all rooms has the lowest construction cost trends. Comparing the directions of the construction cost for each room, it found that the Retail room has the highest construction cost because of the large area, the air ductwork design being complicated, the most material used, and the increased operating cost more to the Café room and the lowest construction cost is the air ductwork for the Yoga room because the small area and the air ductwork design are uncomplicated.

Economic analysis of air ductwork

Analyzing air ductwork economics in the air-conditioning system involves expenses in various fields. In addition, assuming the cost consists of the investment cost, operating cost, electrical energy

cost, and maintenance cost is considered for analyzing the worthiness in terms of economic analysis. Calculated the total cost of five types of air ducts in the fitness center by equation (5) and analyzed the worthiness in terms of economic analysis; the project's duration is ten years, due to the air ductwork older than ten years should be replaced to prevent the damage (Abi Mathew and Thangavel, 2021). Comparing the air-conditioning system with air ductwork and conventional air-conditioning system (no air ductwork) found that the conventional air-conditioning system's total cost throughout the lifetime is high. The air-conditioning system with air ductwork can reduce the total cost throughout the lifetime. The air ductwork with the most increased total cost over the lifetime is the GI Perforated Duct, followed by PVC Canvas Duct and Fabric Duct, respectively. Moreover, the lowest total cost over the lifetime is PID Duct because these air ducts have the lowest construction cost, maintenance cost, and electric energy cost, as shown in Figure 8.

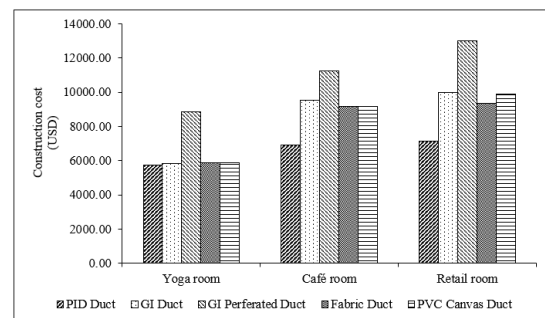


Figure 8. Total cost of air ductwork in air-conditioning system

Comparing the cost of all air ductwork types in the air conditioning system, it was found that the trend of investment cost is the highest, followed by the electrical energy, operating, and maintenance costs. The total cost of the air ductwork project with the conventional air-conditioning system (no air ductwork) was higher than that of using air ductwork because the conditioned area needs an air supply distributed to all, which requires more air conditioning split type. The air ductwork in HVAC requires material to cover the entire air-conditioned area, increasing investment and high electrical energy costs. This system's airflow through the air duct has heat losses and heat exchange between inside and outside, depending on the physical and thermal properties of each air duct's material. Therefore, each air duct type has a different electrical energy consumption to maintain the temperature inside the air duct as designed.

The worthiness analysis of air ductwork in the air-conditioning system.

The variable commonly used to analyze and measure the air ductwork project's worthiness is the discount rate method calculation, in which the principle is to make money's future value the present value. This research calculated the benefit-cost ratio (B/C) to analyze the acceptance of the project. It calculated the payback period to evaluate the appropriateness of the project period.

1. Benefit-cost ratio (B/C); Calculated by equation (7)

$$B / C = \sum_{t=0}^n \frac{B_t(1+r)^{-t}}{C_t(1+r)^{-t}} \quad (7)$$

$$= PVB / PVC$$

When PVB is the present value of benefits (USD/year); PVC is present value cost (USD/year); B_t is benefit component (USD/year); C_t is cost component (USD/year); r is interest rate (%); t is computed year (values from 0 to n); and n is project lifetime (year).

The benefit-cost ratio (B/C) is the variable to show the ratio between the net present value of benefits and the net present value of cost throughout the air ductwork project lifetime; for evaluating whether the project is worthwhile or not, considered as follows:

- If $B/C > 1$, The project is worth investment because it is beneficial or profitable through preliminary evaluation.

- If $B/C < 1$, The project is not worth investing in because the benefit is not worth the investment, or the project loses.

- If $B/C = 1$, The project is suitable for invest.

- Calculated the benefit-cost ratio (B/C) as shown in Table The total cost and benefits results in all useful data for analyzing the worthiness in economic analysis. Comparing the air-conditioning system with and without air ductwork determines that the project's lifetime is ten years. The benefit-cost ratio (B/C) calculated as shown in Table 9.

2. Payback period: The payback period is the variable that shows the number of years in operation that make the net benefit per year equals the initial investment, calculated by equation (8).

$$PBP = P / R \quad (8)$$

When PBP is payback period (year); P is the total cost (USD/year) and R is benefit component (USD/year).

A payback period of the air ductwork project during the project period shows that the net cash inflow from the project is precisely equal to the net cash outflow, which means that the project has no profit and is not lossless. Therefore, this variable is suitable for evaluating the feasibility of a simple investment; the analyzed project should have a payback period within five years to reduce the risk of uncertainty and increase liquidity for the business (Zimon, 2020), as shown in Table 10.

Table 9. Benefit-cost ratio (B/C) of air ductwork in the air-conditioning system

Air duct	Total cost (\$)	Net present value (\$/year)	Electrical energy cost (\$/year)	Electrical energy cost saving rate (\$/year)	Maintenance cost (\$/year)	B/C	
GI Duct	25,341.00	3,609.00	13,175.00	12,718.00	79.00	3.50	worth investment
GI Perforated Duct	33,056.00	4,706.00	15,416.00	9,660.00	1245.00	2.02	worth investment
PID Duct	19,801.00	2,820.00	12,503.00	13,395.00	69.00	4.73	worth investment
Fabric Duct	24,398.00	3,474.00	14,612.00	11,286.00	192.00	3.19	worth investment
PVC Canvas Duct	24,951.00	3,553.00	14,491.00	11,407.00	89.00	3.18	worth investment

Table 10. Benefit-cost ratio (B/C) of air ductwork in the air-conditioning system

Air duct	Total cost (\$)	Electrical energy cost-saving rate (Benefit component) (\$/year)	Payback period (years)
GI Duct	25,340.71	12,717.06	1.99
GI Perforated Duct	33,055.11	9,659.39	3.43
PID Duct	19,800.19	13,394.16	1.48
Fabric Duct	24,397.56	11,285.35	2.16
PVC Canvas Duct	24,950.71	11,406.61	2.19

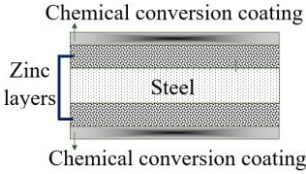
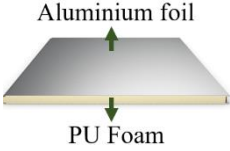
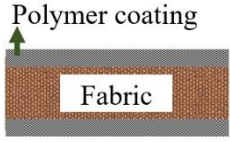
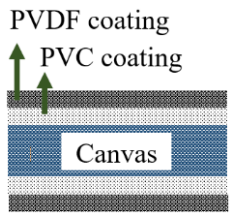
The analysis of the worthiness of the air ductwork in the air-conditioning system, which has a lifetime of 10 years, found that the GI Duct, the GI Perforated Duct, the PID Duct, the Fabric Duct, and the PVC Canvas Duct have the worthiness investment from the electrical energy cost saving rate compare between the air-conditioning system with air ductwork and no air ductwork. Wherewith the benefit-cost ratio is equal: 3.50, 2.02, 4.73, 3.19, and 3.18, respectively, greater than 1. Furthermore, the payback period analysis found that the air ductwork project can be payback within its lifetime. Considering the results of the worthiness of the project, together with the advantages and disadvantages in terms of engineering, we found the PID Duct is the most suitable for investment because this project has the highest benefit-cost ratio, less time for the payback period, the air duct can maintain the temperature inside it with no

insulated, the pre-insulated panel is lightweight, it easy to installation, and it can save electrical energy consumption. As a result, the PID Duct is most suitable for replacement for the air-conditioning system without air ductwork.

Compared the benefits of the new era with conventional ductwork.

The GI Duct and GI Perforated Duct, a conventional material and the PID Duct, Fabric Duct, and PVC Canvas Duct, a new-era material, have different advantages and disadvantages as a guideline for choosing air ductwork applications for the project's owner, as shown in Table 11. All the benefits show that the new era materials have a lower project cost than the conventional materials and more benefits. However, the new-era materials do not have acceptable standards for construction.

Table 11. Guideline for choosing air ductwork applications

Material	Material structure	Project cost (\$)	Energy saving	Duct strength	International Standard
Conventional	Galvanized steel sheet	GI Duct: 25,340.71 GI Perforated Duct: 33,055.11	Low	High	✓
					
New-era	Pre-insulated panel	19,800.19	High	Medium	✗
					
	Fabric				
					
New-era	Canvas	24,950.71	Medium	Low	✗
					

Conclusion

The selection of air duct materials based on ASHRAE and SMACNA standards requires the construction of air ducts from conventional materials (galvanized steel sheets). It has many disadvantages compared with new-era materials (polyester and foam). In the fitness center, the engineer must carefully consider the material selection appropriate as the quality, the investment costs, and the energy conservation of the air-conditioning system by following factors:

- The conventional material air duct is solid and suitable for use inside and outside the building. The new-era materials make air ducts less intense and must only be used inside the building.
- Analyzing the economics of air ducts, it was found that new-era materials air ducts have low cost, high benefit-cost ratio, and short payback periods. Especially the PID Duct.
- The PID Duct has the most benefits in terms of economics and usage advantage.
- The Fabric Duct and the PVC Canvas Duct have similar costs. Both types of air duct materials are characterized as polyester, and they have similar use and installation processes.
- The new-era materials air ducts can save energy, resulting in low electrical energy costs throughout the service life.

Acknowledgement

This research is funded by Kasetsart University through the faculty of engineering at Kamphaeng Saen.

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