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Archimedes Screw Pump Efficiency Based on Three Design Parameters using Computational Fluid Dynamics Software – Ansys CFX

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ARCHIMEDES SCREW PUMP EFFICIENCY BASED ON THREE DESIGN PARAMETERS USING COMPUTATIONAL FLUID DYNAMICS SOFTWARE – ANSYS CFX

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ABSTRACT

Utilization of Archimedes screw pumps as water lifting pumps has become widespread in past decade due to frequent occurrences of floods in Malaysia. The problem of insufficient drainage in various urban areas exacerbates the impact of heavy rainfall, prompting efforts to mitigate this issue with minimal maintenance cost and low impact to the environment. Thus, this study is aiming to study the design parameters of screw pump to obtain the optimal efficiency of the Archimedes screw pump specifically for flood mitigation in Malaysia. The main design parameters affecting pump's efficiency are rotor profile, pitch length, length of the pump, rotational speed, inclination angle, and material selection. However, only three design parameters were considered in the study, that are the angle of inclination, the number of blades, and the angular velocity of the rotating pump. These three design parameters are selected as many previous findings focusing on varying angle of inclination with number of blades with constant rotational speed. Thus, this study will find the highest efficiency when these three design parameters are integrated with variation of rotational speeds at 25, 30 and 40 RPM. Basically, screw pump is designed using SOLIDWORKS and simulations with specific boundary conditions are conducted using the ANSYS-CFX software, which utilizes computational fluid dynamics (CFD) techniques. These boundary conditions are based on previous study by Rosly et al in 2016. The inlet flow rate of 0.002 m³/s and diameter of the screw pump are constant while the other three main parameters are varying within the acceptable ranges which are reported from prior studies. The outcomes found that the highest torque is generated by a single rotating blade at 5.65 Nm which rotates at 30 RPM at 30° angle of inclination. Meanwhile, the highest efficiency of 24.04% is obtained with a single rotating blade at 40 RPM with 20° angle of inclination. Based on the findings, it is concluded that these three main design parameters of screw pump may not be sufficient to obtain the optimal efficiency for the specific boundary conditions used in the simulation study. Thus, several combinations of design parameters should be considered in the future to increase the screw pump's efficiency.

Keywords: Archimedes screw pump; computational fluid dynamics; efficiency; angle of inclination; number of blades; angular velocity.

INTRODUCTION

The Archimedean screw pump is said to be the oldest water pump utilized [1] for liquid transportation. Archimedes screw pumps (ASP) may be operated at all flow rates, from zero to full capacity, with no risk of excessive wear or even damage. Until today, ASP is still



commonly used for dewatering low-lying areas and wastewater treatment facilities [2]. On the hand, Yoosef, Doost, A and W.-D. Lubitz have also figured out Archimedes Screws Turbines (AST) is considered as a new type of mini hydroelectric power plant that can be used in a low headed site. This is because they can operate in a wide range of water flows from 0.01 to 14.5 m s^{-1} and heads of 0.1m to 10 m , including heads, which are not ideal for traditional turbines and not occupied by high performance technologies [3]. Basically, there are two different kinds of screw pumps: open and enclosed. The open screw pump is renowned for its reliability and simplicity. Even though these pumps require very little maintenance, pumps can be made even more robust. This will reduce wear and tear even more if the lower bearing is made with permanently greased lubricated roller bearings or sleeve bearings. Compared to open screw pumps, enclosed screw pumps are simpler to install because they are enclosed inside a tube and don't require a steel or concrete trough. It can be utilized if you need a replacement right away and don't have the time to set up a trough [4].

ASP possesses a straightforward and robust design, operating at a slow speed. Its simplicity, open structure, and slow rotation contribute to its high reliability, allowing it to function as a heavy-duty pump with minimal wear and tear, then enabling long-term operation. The pump's open structure and spacious passage between the flights allow it to pump water containing low-head debris without requiring a coarse screen before the pump [5]. The effectiveness of pumps or turbines can be studied through Computational Fluid Dynamics (CFD). Gap leakage, overflow leakage, and inner bucket flow patterns can all be analyzed using CFD, which can isolate factors and offer a significant deal of information. A relative error in simulations of less than 1% compared to experimental data [6]. By understanding the geometrical parameters of ASP, the mechanical efficiency of ASP can be fully maximized. The parameters are rotational speed, slope angle, and number of blades [10-12]. A study discovered that increasing mass flow rate and the number of blades increased torque and efficiency while increasing angle of inclination caused it to decrease [7]. Lubitz et al. stated that increasing the angle of inclination would greatly reduce the efficiency of screw since the gap leakage would increase [8]. According to Abdul, Dr. Binu, and Dr. Jeoju's findings, the behaviour of the efficiency and the torque produced is directly proportional to the mass flow rate [7]. Nagel figured out the theoretical investigation using the graphical method, practical measurements on full-scale plants, and results of model tests have demonstrated that the shaft tube diameter to the external diameter of the screw ratio must be between 0.45 and 0.55 to achieve maximum efficiency and, consequently, optimal deliveries [1,12-14]. Based on field experience and the design and operation of Archimedes screws, it is recommended that the rotating velocity of the screw in revolutions per minute should not exceed $50/D^2/3$, where D is the cylinder's outer diameter [2]. The buckets would not fill if the screw were twisted too quickly because of turbulence and sloshing, hence will cause the screw to churn the water to the bottom reservoir rather than raise it [2,13-15]. Meanwhile, mild steel is commonly utilized for fabricating pressure vessels as well. Its ability to withstand elevated temperatures and pressures makes it a suitable choice for safely containing diverse liquids and gases even in demanding circumstances [9,15-16].

Therefore, the purpose of this study is to replicate the design concept of ASP, series of simulations are performed by considering the angle of inclination, and the number of blades on the screw. These simulations are conducted under conditions of constant flow rate and constant diameter ratio. Secondly, this study is also aimed to determine the efficiency of the ASP in terms of the angle of inclination, number of blades and angular velocity of the rotating pump to examine the best design parameter based on the highest efficiency of ASP. The result is expected to increase the pump's efficiency when inclination angle is decreased while rotational

speed is increased. This is due to low gravitational force is obtained at low inclination angle, thus minimal hydraulic power requires to rotate the screw pump to transport water.

METHODOLOGY

Screw pump efficiency is affected by several design parameters which are rotor profile, pitch length, length of the pump, rotational speed, inclination angle, and material selection. However, only three design parameters were considered in the study, that are the angle of inclination, the number of blades, and the angular velocity of the rotating pump. These three design parameters are selected as many previous findings [7,10-12] were focusing on varying angle of inclination with number of blades with constant rotational speed which the highest efficiency can be obtained in this study with different configurations of these three parameters simulated using ANSYS-CFX.

Detailed screw pump efficiency calculations are discussed in the section of theoretical equations which efficiency is determined by comparing power generated by screw pump driven by electric motor (ie mechanical power) with power generated by water (ie hydraulic power). The mechanical power is calculated as the product of the total torque and screw rotational speed. Meanwhile, hydraulic power is a function of density of water, head difference, and the water flow rate through the screw. The water flow rate of one bucket of water is determined by water velocity, number of blades, screw pitch and volume of bucket. Thus, design parameters of screw pump such as screw rotational speed and number of blades that are independent and directly contribute to mechanical and hydraulic power. It clearly stated that both design parameters are independent of other design parameters of screw pump. For example, if screw pitch is chosen, the diameter and the length of screw will be affected. Thus, to simplify the investigation, this study is solely focusing on the independent design parameters that directly affecting the screw pump's efficiency. Meanwhile for inclination angle is indirectly affecting the hydraulic power of screw pump as it proportional to the head difference. Theoretically, by increasing the inclination angle, the head difference is increased which consequently increases the water gravitational force. In response, this will affect the efficiency of screw pump as high torque is required to rotate the screw.

The flowchart illustrated in Figure 1 represents the overall flow of study, which starts with the designing stage. Based on prior design concept [10] three angles of inclination (20° , 30° and 35°), with three variation number of blades (1, 2 and 3) on the screw are varied accordingly. Then series of simulations are performed by considering three different screw rotational speeds of 25 RPM, 30 RPM and 40 RPM which have been applied to smaller size pump of 1 meter in length [11]. The chosen design parameters are to find the highest efficiency which could be applied to small applications (ie home usage) such as in rural areas for flood mitigation. In Netherland, massive size of screw pumps up to 6 meter in length are used for flood mitigation [3], however it is complicated to apply this type of pump in Malaysia due to manufacturing and maintenance costs on top of high pump loss (reducing its efficiency) when pump operates at high rotational speed.

Thus, this study is focusing on simulations which are conducted under conditions of constant flow rate and constant diameter ratio by using ANSYS CFX. Lastly, the efficiency of the ASP in terms of the angle of inclination, number of blades and angular velocity of the rotating pump are calculated by using theoretical equations to determine the best design parameters based on the highest efficiency of ASP.

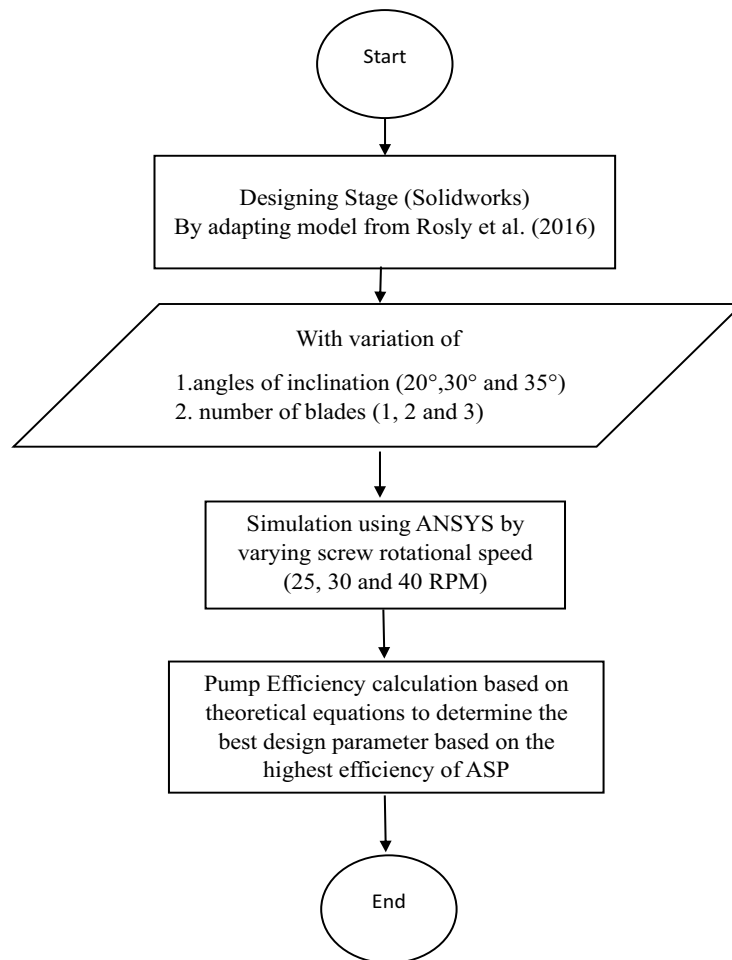


Figure 1. Overall study flowchart

Designing Stage

The Archimedes screw pump (ASP) created in a 3D geometric model using SOLIDWORKS which is a computer-aided design (CAD) software. Three different blades are constructed, one with a single rotating blade, another with two rotating blades, and lastly, three rotating blades. Then, these blade configurations are constructed based on different inclinations angles of 20°, 30°, and 35°. Once the design is completed and finalized, the model is imported into ANSYS-CFX and simulations will be running according to the boundary condition setting based on prior study.

Table 1. ASP parameters and dimensions.

Parameter	Dimension (mm)
Length, L	1140
Outer radius, r_o	110
Inner radius, r_i	100
Shaft diameter, D	108

As mentioned in Table 1, ASP parameters used in this study are based on the previous study of Rosly et al. in 2016 [10]. The geometry model of ASP is drawn using SOLIDWORKS software which is a computer- aided design (CAD) software as illustrated in Figure 2.

Table 2. ASP design parameters.

Parameter	Specifications
Number of blades, N	1,2 and 3
Angle of inclination, α	20°,30° and 35°
Angular velocity, ω	25,30,40 (RPM)

Meanwhile, Table 2 describes three design parameters which are selected to be studied to analyze the screw pump's efficiency. Each parameter has distinct effect at different levels. Thus, this study is mainly focused on these three specific design parameters which are the screw rotating speed (ω), angle of inclination (α), and the number of blade (N) which affects ASP efficiency.

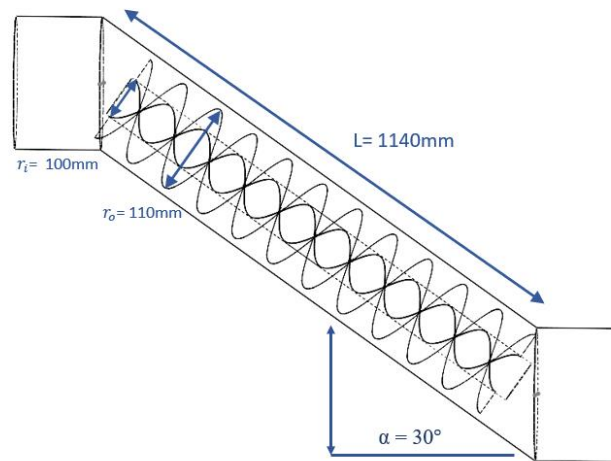


Figure 2. ASP model in SOLIDWORKS

Simulation of Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) can be used to create fluid motion simulations. The fluid flow motion may be solved and studied using numerical methods and algorithms included in CFD. After designing the model, the model is imported into ANSYS for simulation purposes. By using ANSYS Software, Fluid flow CFX simulations are chosen particularly for this study. The material of the screw is set to be Mild Steel and the fluid is the mixture of water and air by setting up multiphase model with Volume of fluid as homogenous model. The boundary condition used in this simulation is set to be in steady state flow. The inlet velocity is constant ($0.002 \text{ m}^3/\text{s}$) with a condition of no slip wall at the blade and its casing, whereas the outlet pressure is 0 Pa whereas the screw rotational speed varies from 20 RPM to 40 RPM. Furthermore, simulation fluid is set as water enters the ASP at 70% and 30% is considered as air, this assumption is important because in practice the ASP is not able to fully submerge into

the water because only fraction of water is contained within the ASP. The turbulence model will be the standard k-epsilon model with 5% medium intensity and the fluid pair of water and air surface tension coefficient of 0.072 n/m. Furthermore, the interface method is employed to establish a connection between domains which are the rotating domains and stationary domains. This is mainly due to ensure that the boundary conditions are reasonably set, otherwise the software may default on the settings, and this may cause potentially inaccurate outcome. The procedure above is repeated by changing the design parameters of ASP from 1 blade to 2 and 3 blade respectively. This repeatability studies are purposed constructed to determine the optimum design parameter that affects the efficiency of Archimedes screw pump. The boundary conditions are outlined as in Table 3.

Table 3. ASP model boundary conditions.

Boundary condition	Specification
Pump material	Mild Steel
Fluid material	70% water, 30% air
Inlet velocity	0.02 m/s
Pressure outlet	0 Pa
Water density	997 kg/m ³

Theoretical Equations

Based on the results obtained from series of simulation, the hydraulic power and mechanical power of the ASP are manually calculated based on the equation 1 and equation 2 as stated below:

$$P = \tau \cdot \omega \quad (1)$$

Where: τ is the torque generated by the ASP in Nm

ω is the angular velocity of rotating pump in radian per second

$$P_{hyd} = \rho \cdot g \cdot Q \cdot H \quad (2)$$

Where: ρ is the density of water in kg/m³

g is the gravitational force in m/s²

Q is the volume flow rate in m³/s

H is geodetic head difference in m

After gaining the mechanical power and hydraulic power of ASP, the efficiency is calculated by taking the ratio between equation 1 and equation 2.

$$\eta_{th} = \frac{P}{P_{hyd}} \quad (3)$$

Where: P is mechanical power in W

P_{hyd} is hydraulic power in W

RESULTS AND DISCUSSION

The design of the Archimedes screw pump (ASP) chosen in this study is based on the geometry used from previous researchers [10-12]. The simulations are used to examine the impact of these three design parameters, namely the slope inclination angle (α), the number of bladed screws (N), and the angular velocity (ω). The main objective is to investigate the effect of these three design parameters that affect the efficiency of the Archimedes screw pump (ASP). A total of 27 simulations are conducted in this study after completing the design of ASP model. These simulations involved variations in the number of bladed screws (N), with values of one, two, and three, as well as changes in the slope inclination angle (20° , 30° , and 35°) and the angular velocity (25 RPM, 30 RPM, and 40 RPM). The result of the study is presented and discussed with a focus to determine the best efficiency of the Archimedes screw pump (ASP). Figure 3 until Figure 5 shows the efficiency of ASP with respect to the number of blades.

The Efficiency of Archimedes Screw Pump

In this study, the water flow rate is maintained at a constant level which is $0.002 \text{ m}^3/\text{s}$. Consequently, the amount of water flowing through the screw blade remained consistent for all angle of inclination and rotational speed of the pump.

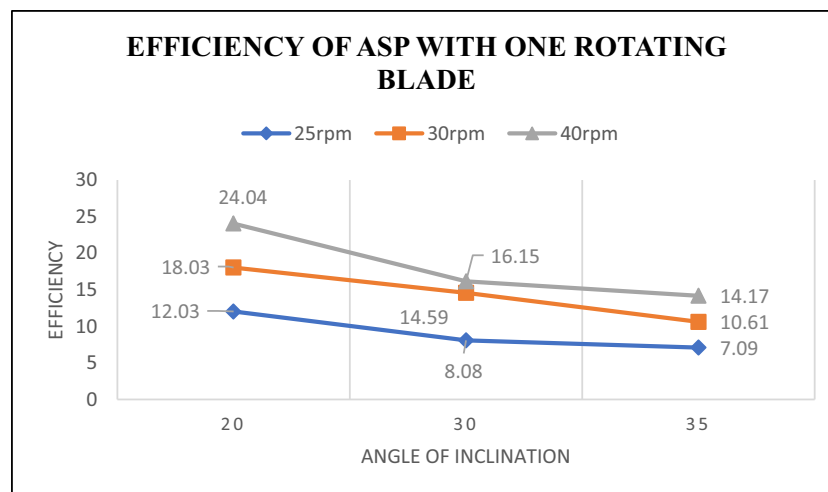


Figure 3. Efficiency of ASP with a single rotating blade.

The efficiency of ASP is influenced by the angle of inclination for a single rotating blade. It is observed that the efficiency of the ASP is directly proportional to the angle of inclination. The maximum efficiency, reaching 24.04%, was attained at an angle of inclination of 20° and an angular velocity of 40 RPM. On the other hand, the minimum efficiency, measuring 7.09%, was recorded at an angle of inclination of 35° and an angular velocity of 25 RPM.

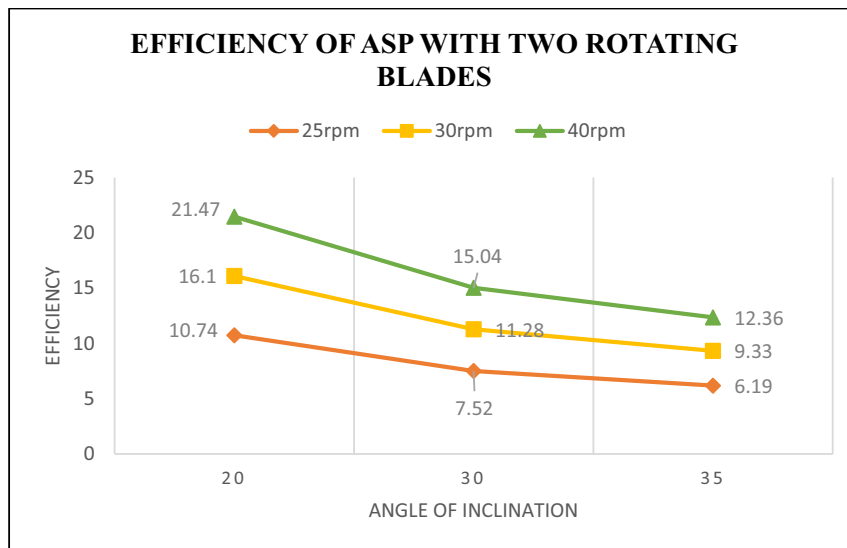


Figure 4. Efficiency of ASP with two rotating blades.

The maximum efficiency for two rotating blades is 21.47%, achieved at a 20° angle of inclination with an angular velocity of 40 RPM. The minimum efficiency for two rotating blades configuration is 6.19%, observed at a 35° angle of inclination and an angular velocity of 25 RPM.

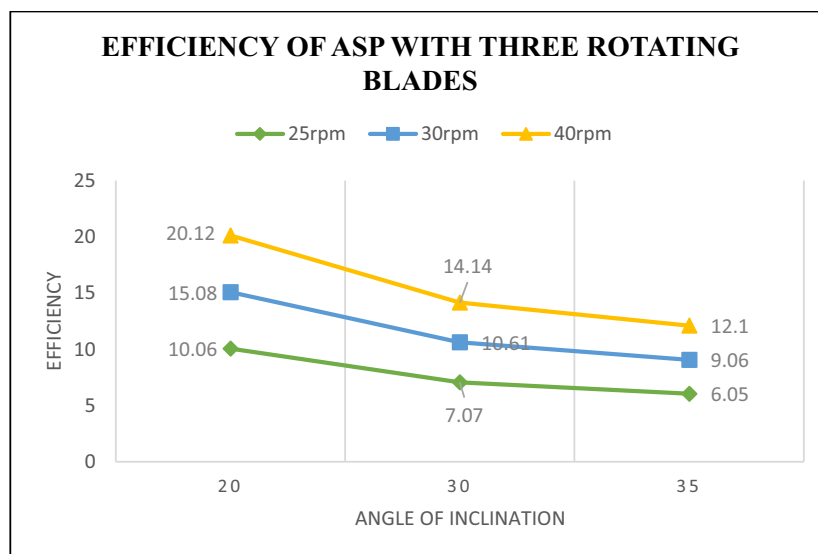


Figure 5. Efficiency of ASP with three rotating blades.

On the other hand, the three rotating blades achieve a maximum efficiency of 20.12% at the same 20° angle of inclination at 40 RPM. The three rotating blades configuration achieves a minimum efficiency of 6.05% at a 35° angle of inclination and 25 RPM.

The efficiency of the ASP has been evaluated through parameter studies, as presented in Figure 5. The results are categorized into three sections based on the rotational speed: 25

RPM, 30 RPM, and 40 RPM. In this study, it is identified a maximum efficiency is 24.04% and a minimum efficiency is 7.09%. It was observed that the highest efficiency was achieved at a lower angle of inclination. This can be attributed to reduced power losses and an increase in the head difference. These factors significantly impact the calculation of hydraulic power, as the head difference and angular velocity play crucial roles in determining the pump's efficiency. By having an optimal slope inclination angle is crucial because the water inlet flowing through the blades exerts pressure, torque, and power on the ASP, ultimately influencing its efficiency [8].

Although, in theory it is expected highest efficiency is obtained when screw pump is at low inclination angle as the pump losses due to gravitational force is minimal which minimize the hydraulic power as mechanical power is high due to high rotational speed generated by electrical motor which it will consequently elevate the screw pump efficiency in return. This study proves that at low inclination angle, 20° at 40 RPM with single blade the highest efficiency of 24.04% is obtained. However, it is necessary to validate this finding within experimental setup before it can practically be used in any water transportation application especially in flood mitigation and irrigation for single household usage as the size of the pump is small compared to industrial usage which has been widely used in other countries such as Netherland, United Kingdom, China, Japan, and South Korea in flood mitigation and irrigation system.

CONCLUSIONS

This study demonstrates method of using CFD simulation to predict the power output and efficiency of an ASP (Archimedean Screw Pump) before any experimental procedure take place. The mechanical power output of one-, two- and three- ASP blades were determined by simulated torque generated through CFD simulations with fixed flow rate of 0.002 m³/s. These variations number of blades are at inclined angle of 20°, 30°, and 35° with rotational speed of 25, 30 and 40 RPM. Significant results indicate that the concept design of the ASP achieved its maximum power output at a rotating speed of 40 RPM in 20° angle of inclination with a single rotating blade, thus indicating the highest efficiency. As a result, we can conclude that the high angular velocity for rotating speed could produce higher efficiency.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

W. L. Chan: Design, Simulation and Writing-Original draft preparation. U. K. Jamaludin: Conceptualization, Investigation, Writing-Reviewing, Supervision, Validation and Editing. N.S. Azahari: Methodology, Simulation, and Reviewing.

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