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STUDY ON ROBOTS FAILURES IN AUTOMOTIVE PAINTING LINE

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ABSTRACT

The increasing number of robots in the automotive industries improved the production throughput, quality and safety. More robots encountered more failures. This paper analyses the probability of failures of robot at components level in automotive top coat painting line. Timely analysis of failures could reduce the downtime. The objective of this research is to establish replacement strategy for replacement of robots due to component failures. The approaches used in this research are 1) analysing failures data, mean time between failures (MTBF) and mean time to repair (MTTR), 2) computational of the defender maintenance annual cost and challenger minimum cost of operating. The probability of failures of robots in the top coat system were mainly due to servo motor with 0.20 probability of failure is 0.20. From the analysis the robot with lowest MTBF was 5280 hours. Replacement strategy was established using marginal cost (MC) and equivalent uniform annual cost (EUAC) analysis was done for the robot and the potential candidate for replacement. Result from the case study, the cost of maintaining defender at year 6 was Malaysian Ringgit 825,000, while the minimum cost of annual operating of challenger was Malaysian Ringgit 766,000. It is noted that the cost of the maintaining the defender was higher than the minimum annual operating cost of challenger at year 6. Hence, replacement of defender should be made by end of year 5.

Keywords: replacement analysis, mean time to failures, mean time to repair, marginal cost, equivalent uniform annual cost margins.

INTRODUCTION

Robots are the main equipment for automotive industry specifically operation of painting line. In the case of robots for painting operation, the failure do occurred where affect the production throughput. Due to robots are required to perform in a very high precision and high repeatability manners, the consistency of the functional is crucial. In any cases, failures or degradation of functionality are jeopardizing the production throughput due to downtime.

In most cases, when robots failed, the failure is due to subsystem failure. In some cases, the subsystem can be repaired and some cases the subsystem has to be replaced. The subsystem component in the robot system is inter-connected and it is connected in series configuration in the sense of reliability model. The main issue of replacing or repairing of the subsystem components is no specified guideline established which assist minimize the robots ownership.

The objective of this study is to develop a replacement model for robots in order to avoid major downtime due to unplanned failure. The replacement model for robot in automotive assembly plant was developed based on MTBF factor, life cycle cost factor and economic factor [1, 4]. The balancing of these two factors decided the decision making for replacement of subsystem of specific robot. This is to ensure by minimizing the repairing cost or replacement cost.

This study incorporated the study of robot failures data, MTBF, MTTR, MC and EUAC. It is to be achieved by dividing the objective into two (2) sub-objectives.

a) Identified the candidate for replacement by analyzing the failure data and MTBF of each robot. Upon identifying the most problematic robot system, the subsystem levels as well as the components level of robots were studied.
b) Determined when to replace by analyzing MC of current robot and EUAC cost for candidate robot replacement.

The actual maintenance data of failures and the frequency of failures were acquired. Economic life cycle analysis will determine when replacement of robot justified [4]. It is expected that the results of the study possibly will assist painting shop management to justify the decisions on the robot life cycle based on failure rate, MTBF and yearly maintenance cost as well as the robot life cycle economic analysis.

The scope of the study is to analyse the failures data, MTBF and MTTR as well the replacement analysis of robots in the automotive plant. Robots were introduced in the automotive industry could be as many as 150 units to 200 units for 150,000 units to 200,000 units per year of plant capacity. There are 156 robots distributed in stamping shop, body shop, painting shop and assembly shop. The study covered 10 years product life cycle of the robots. The failures were based on robots used for saloon assembly model range 1000cc to 2000cc and the assembly plant capacity of the production assembly line was approximately 180k units per year.

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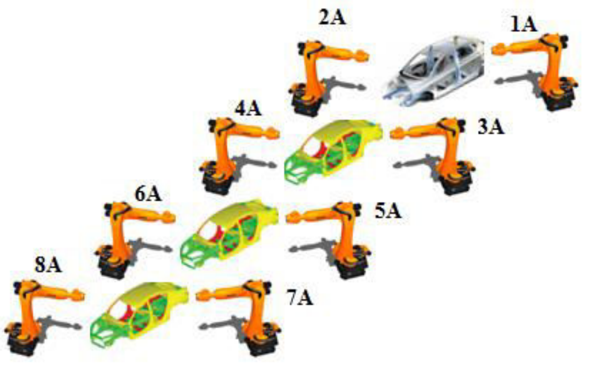

Figure-1. Schematic diagram of top coat robotic system.

There are two subsystems in the top coat line in automotive assembly plant namely top coat 1 and top coat 2 as shown in Figure-1. Top coat consists of base coat and clear coat. The base coat is a colour coat while the clear coat is the most outer layer of automotive coating. This coating is purely a cosmetic reason of a car which various coloursto accommodate customer demands. Most automotive plants use pre-programmed robotic arm for spraying application of these coating.

BASIS OF THE MODEL

The focus of this model is on robots at the painting line of an automotive plant. The maintenance data of the robots at the painting line were used for the model. The main issue in maintenance is to determine whether equipment is repairable or non- repairable elements. This has bearing to type of analytical equations to be used for the model. For the case of robots, it is classified as repairable equipment as it is the practice of industries. However if the robot is broken up into subsystems, the subsystems can be classified either as repairable and non-repairable elements.

As illustrated in Figure-2, the robot system consists of five major subsystems, namely the controller, the robot arms, the end effectors, the drive mechanism and the sensors [2,3]. Each of the subsystem in turn consists of components which are inter connected with each other while performing its task. Failure of the subsystem resulted from the failure of one of the components. The subsystem failure could then result to robot failures; hence, it is essential to ensure the components of the robot system are in good condition.

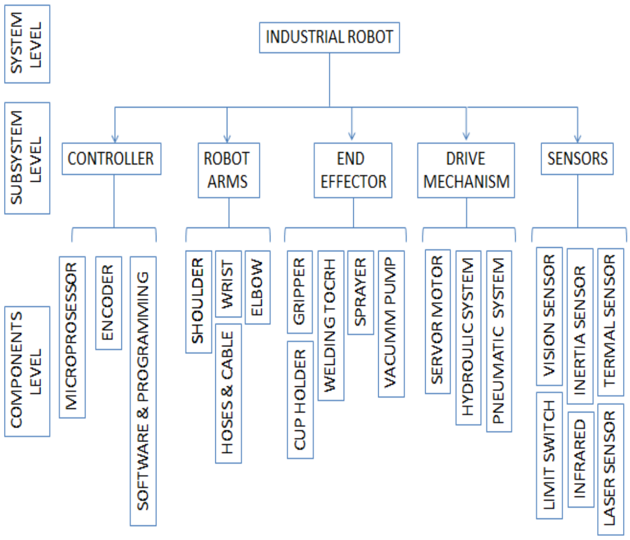

Figure-2. Industrial Robot System broken up into subsystem and components level.

The controller is the brain of the robot system. The microprocessor, encoder as well as the software and programming in the controller are interconnected in the performing the given instruction to perform a particular task [3].

The hardware side of controller is repairable elements. However, if it is related with software such as microprocessor and encoder it is then non-repairable elements. The industrial practice is that, faulty microprocessors are replaced with new microprocessors. The sub components such as input and output relays in the controller are also classified as non-repairable elements.

In the case of programming error due to external cause such as main power off, the error code is repairable through the interface analysis using pendant or control panel of the controller.

The robot armsfunction as manipulator mechanism which consists of shoulder, elbow and wrist. The supporting components such as hose and cable are parts of the manipulator mechanism. This mechanism provided the lifting power of the robots. The elements of weight, shape, direction of movement, and repeatability determine the size of the robots [3].

The main components of robot arms are classified as repairable elements. The problematic area such as joint between shoulder and wrist can be repaired. Whereas, the sub component of the robot arms such as hose and cable are non-repairable elements. The practice was broken hose replaced with the new hose.

The end effectors are mechanism which is attached to the wrist of the arm of the robot. Its function is to serve either to handle a part with loading and unloading capability or to process part. It is normally called a finger. There are various type of end effectors such as gripper, cup holder, welding torch, welding gun, sprayer and vacuum pump [3].

The end effectors are mechanically structured. The gripper, welding torch, welding gun are reparable units. In the case of robot painting line the sprayer is used and it is categorized as repairable element. In the industrial practice, the sprayer was changed with the new one when it is faulty as the process of the repairing is taking longer time compared with replacing it with a new sprayer.

The drive mechanism consists of hydraulic mechanism, pneumatic mechanism and servo mechanism. Motor is a device which converts electrical energy to mechanical energy. Most of the current systems are using servo motor as a drive mechanism. It is also the similar case for the motor used in industrial robotics. The motor used is servo motor. Due to the innovation of latest robots structure, the servo motor with Alternating Current AC or Direct-Current DC power source is widely used. It is compact in size and the payload capability is compatible with hydraulic counterpart. The quantity and the specification of servo motor in robots vary depending on the payload and degree of freedom of the robots [3].

In this research, the focus is on the servo motor mechanism. This is due to all robots in the automotive industry are the industrial robots which assist the labour to complete a task are using servo motors. Keeping the servo motor in running condition is essential. Failure on the functionality of the servo motor will lead to the whole robot system shutdown. It is connected in series configuration with other components of robot system.

Faulty servo motor can be costly in term of replacement cost of the whole unit or repair cost of the servo motor itself. As industrial practice servo motor is repairable. The elements of servo motor consist of stator, rotor and microprocessor. Due to the cost of loss in opportunity is higher than the cost of servo motor itself, the replacement is more justified by keeping the servo motor as a spare part.

The most common fault of the servo motor is overheating, over current and electrical surges, moisture, dirt and vibration. The environments of the robots installed in the industry play important roles for the maintaining the system. Certain area of the work cell is exposed to the dust, dirt and heat, such as painting line in automotive industry which would lead to major fault on the robotics system.

The sensors can be divided into 3 classes; internal sensors, external sensors and interlock sensor. Most of the sensors are the transducer type and some are limit switch type. Various types of sensors exist in the industrial robots such as vision sensors, thermal sensors, laser sensors, inertia sensors and infrared are classified as non-repairable elements [3].

Due to many repairable and non-repairable components which are inter-connected in the robotics system, the analysis in term of ownership costing is essential. The breakdown could occur at any time due to external or internal factors. It is vital to analyse the failure rate, mean time between failure and mean time to repair of the repairable elements.

The robotic system life cycles in most cases are based on supplier recommendation is between 10 years to 15 years. The recommended MTBF as for Fanuc robot and ABB robots are 60,000 hours and 80,000 hours respectively based on continuous operation.

In this study where the service life of the robotics system reaches 10 years, it is recommended to analyse the MC of the robots but for the case of robot to be purchased, it is recommended to analyse the EUAC. This is to take into account the technology factors.

METHODOLOGY

The methodology framework consists of three main steps as per Figure-3.

The study started with gathering the historical data of the robots which was collected from the actual maintenance data from the automotive plant. The data was organized and analysed from the maintenance sheet.

Step 1is the process of identifying and classifying of robot subsystem into repairable category and non-repairable category. It is consists of;

a) Identify the system and subsystem of robot.
b) Classify the subsystem in repairable and non-repairable.

Step 2 is the process to study the MTBF of the subsystem that give the higher probability of failures. The incorporation of MTBF and annual costing are tabulated for each individual robot system.

a) MTBF and MTTR analysis
b) Annual Costing

The step3is a process to study the economic factor of robot system;

As the robot system which having the recurrence problematic failures of subsystem, the replacement analysis using marginal cost analysis of defender was analysed. The evaluation of challenger EUAC was established and finally comparing the marginal cost of defender with min EUAC of challenger [4]. The economic data were used for life cycle justification of robots replacement strategy.

a) To develop MC analysis for the robot that needs to be replaced;
b) To develop EUAC model for the robot that can be replaced the defender;
c) To compare the MC of defender with EUAC of challenger;

Finally, the recommendation to the management decision for further action.

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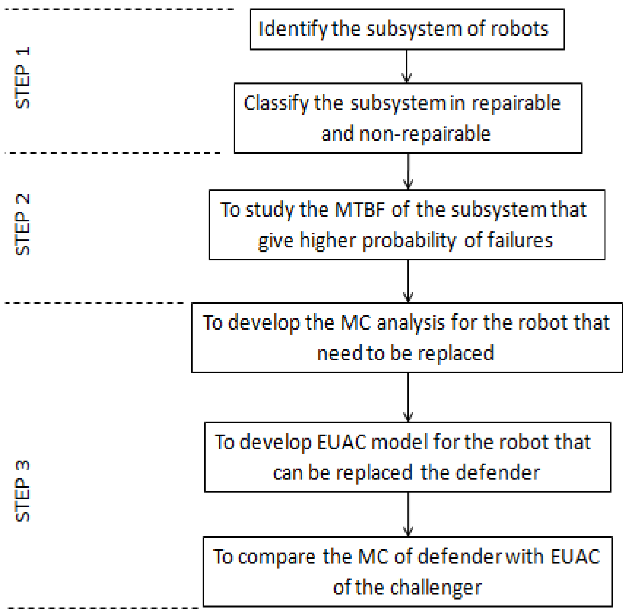

Figure-3. Research methodology framework.

THE QUANTITATIVE MODELING

a) MTBF and MTTR quantitative analysis

In the analysis of this research, the equation (1) and (2) were used for evaluation of MTBF and MTTR;

$$MTBF = \frac{T(t)}{r} = \frac{TotalOperatingHours}{Numberoffailures} \quad (1)$$

$$MTTR = \frac{Productiondowntime}{Numberofrepairs} \quad (2)$$

b) Annual cost of failures

The annual cost of failures was calculated using equation (3),

$$C_y = \frac{(C_G)(TOT)}{(MTBF+MTTR)} \quad (3)$$

Where

C_y = Annual Cost of failures
C_G = Cost per failure event
TOT = Total hours operation per year
MTBF = Mean Time between Failure
MTTR = Mean Time to Repair

c) Annual expenses

As in industrial practice, the equation (4) was adopted for electricity tariff calculation

Cost (RM / Month) = Electric Tariff (RM / kWh) x Robot Power Rate (kW)x(24 hours / Day) x (30 days / Month)(4)

d) Economic replacement assessment

Economic decision making on the robot lifecycle is essential for the replacement analysis. The marginal cost analysis for defender and marginal cost and EUAC analysis for challenger analysis were computed using Table-1 and Table-2 respectively. The templates were modified from [2] by incorporation of yearly cost due to maintenance and loss of opportunity to the original templates. The modified templates evaluating MC consists of market value, loss in market value, cost of capital, annual expenses, yearly cost due to maintenance, loss of opportunity and marginal cost. While, the modified template for evaluating EUAC consists of market value, loss in market value, cost of capital, annual expenses, yearly cost due to maintenance, loss of opportunity, marginal cost and EUAC.

In order to evaluate the EUAC of the challenger, below equation was adopted [4],

$$EUAC_k = \left[\sum_{j=1}^{k} TC_j(P/F, 10\%, j)\right](A/P, 10\%, k)(5)$$

The economic data were further acquired for the replacement analysis. From the initial capital investment, depreciation value and annual expenses, the marginal and EUAC costs were calculated.

The computational of column 5 and 6 were as equation (4) and equation (3) respectively.

Table-1. Marginal cost for defender.

a) Marginal cost for defender

(1) End of Year *k*	(2) MV, End of Year *k*	(3) Loss in Market Value (MV) during Year *k*	(4) Cost of Capital = 10% of Beginning of Year MV	(5) Annual Expenses (E*k*)	(6) Yearly Cost due to maintenance (Cy)	(7) Loss of Opportunity (Lo)	(8) [=(3) + (4) + (5) + (6) + (7)] Marginal Cost for Year (TC*k*)
0	x0	-	-	-	-	-	-
1	x1	a1=x0-x1	b1=10%*x0	c1	d1	e1	a1+b1+c1+d1+e1
2	x2	a2=x1-x2	b2=10%*x1	c2	d2	e2	a2+b2+c2+d2+e2
3	x3	a3=x2-x3	b3=10%*x2	c3	d3	e3	a3+b3+c3+d3+e3
4	x4	a4=x3-x4	b4=10%*x3	c4	d4	e4	a4+b4+c4+d4+e4
5	x5	a5=x4-x5	b5=10%*x4	c5	d5	e5	a5+b5+c5+d5+e5
6	x6	a6=x5-x6	b6=10%*x5	c6	d6	e6	a6+b6+c6+d6+e6
7	x7	a7=x6-x7	b7=10%*x6	c7	d7	e7	a7+b7+c7+d7+e7
8	x8	a8=x6-x8	b8=10%*x7	c8	d8	e8	a8+b8+c8+d8+e8
9	x9	a9=x8-x9	b9=10%*x8	c9	d9	e9	a9+b9+c9+d9+e9
10	x10	a10=x9-x10	b10=10%*x9	c10	d10	e10	a10+b10+c10+d10+e10

Table-2. Marginal cost and EUAC for challenger.

b) Marginal cost and EUAC for challenger

(1) End of Year *k*	(2) MV, End of Year *k*	(3) Loss in Market Value (MV) during Year *k*	(4) Cost of Capital = 10% of Beginning of Year MV	(5) Annual Expenses (E*k*)	(6) Yearly Cost due to maintenance (Cy)	(7) Loss of Opportunity (Lo)	(8) [=(3) + (4) + (5) + (6) + (7)] Marginal Cost for Year (TC*k*)	(7) EUAC through Year *k*
0	x0	-	-	-	-	-	-	-
1	x1	a1=x0-x1	b1=10%*x0	c1	d1	e1	a1+b1+c1+d1+e1	EUAC1
2	x2	a2=x1-x2	b2=10%*x1	c2	d2	e2	a2+b2+c2+d2+e2	EUAC2
3	x3	a3=x2-x3	b3=10%*x2	c3	d3	e3	a3+b3+c3+d3+e3	EUAC3
4	x4	a4=x3-x4	b4=10%*x3	c4	d4	e4	a4+b4+c4+d4+e4	EUAC4
5	x5	a5=x4-x5	b5=10%*x4	c5	d5	e5	a5+b5+c5+d5+e5	EUAC5

CASE STUDY

Identified and grouped the robots in automotive assembly line. Focus analysis was for top coat line consisting of 8 robots; 4 robots in base coat and 4 robots in clear coat as shown in Figure-1.

The individual robots in the top coat line were referred as system, whereas the component level of the robot such as controller, robot arms, end effectors, drive and sensors are referred as subsystem.

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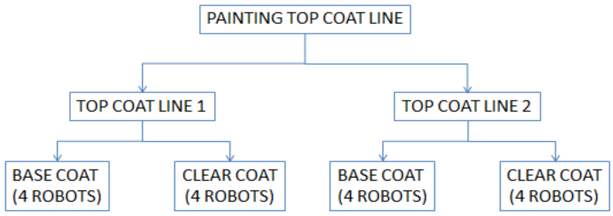

Figure-4. System level representatives.

The subsystem level robots consisted of 5 major elements that build the system level robot as shown in Figure-4.

a) **Controller:** Consisted of components such as control panel, encoders, limits switch, microprocessors, software and programming.
b) **Robot arms:** Consisted of supporting subsystem components such as shoulder, wrist, elbow, hose and cable.
c) **End effectors:** Consisted of supporting subsystem components such as gripper, cup holder, welding torch and vacuum pump.
d) **Drive:** Consisted of supporting subsystem components such as servo motors, hydraulic system and pneumatic system.
e) **Sensors:** Consisted of supporting subsystem components such as vision sensors, infrared, inertia sensors, laser sensors and thermal sensors.

RESULTS AND DISCUSSION

In term of robot as a system, it was categorized as repairable element. While at subsystem level there were repairable and non-repairable elements. There are five subsystems; 1) controller, 2) robot arms, 3) end effector, 4) drive mechanism, and 5) sensors.

Each of subsystem was classified either as repairable or non-repairable based on the classification of major components in the subsystem itself either repairable or non-repairable. For example the proximity sensors in the subsystem sensor were classified as non-repairable elements. From the industrial experience, the sensors were replaced immediately once faulty. The servo motor was classified as repairable element since it could be repaired either in the plant or at the supplier location. Based on practices at the plant, the classification of the elements either repairable or non-repairable are shown in Table-3. The table are also included the probability analysis of failures for each components in the subsystem.

Table-3. Probability of failure of components.

Subsystems	Components	ELEMENTS	PROBABULITY OF FAILURE
Controller	Encoder	NR	0.08
	Connector	NR	0.04
	Limit Switch	NR	0.08
	Computer Monitor	R	0.04
	Data Memory	R	0.08
	Cascade Electronic	NR	0.08
	Pulse Coder	R	0.04
Robot Arms	Hose Thinner	NR	0.08
	Cable	NR	0.08
End Effector	Cup Holder	R	0.04
	Sprayer	R	0.04
Drive	Servo Motor	R	0.20
	Servo Amplifier	R	0.12
Sensors		NR	0.00

In order to assess the replacement of the robot of the automotive assembly plant in the painting line, the replacement model framework was proposed. The replacement model framework is illustrated in Figure-5.

The main principle adopted for the proposed model was to keep and operate the existing robot as long as the MC of the defender was less than or equal to EUAC of the proposed new robot [4].

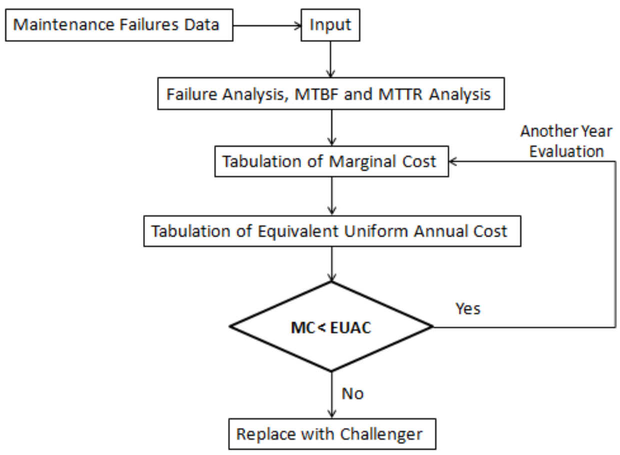

Figure-5. Replacement model framework.

Upon completing the failure data, MTTR and MTBF analysis using the equation (1) and (2), the third robot in the subsystem of robotic system in production line was found to have the lowest MTBF which was 5280 hours.

These findings could assist the evaluation in terms of tightening up the maintenance schedule or carry out the replacement of the robot. In this study the next level of analysis is the replacement analysis by evaluating the defender MC and the challenger EUAC.

The computational of defender MC and challenger EUAC are tabulated in Table-4 and Table-5 respectively. The equations used for defender and challenger MC computation are incorporated in both tables. Equation (5) was used to calculate the EUAC of challenger.

The EUAC of challenger at year 4 was Malaysia Ringgit 766,000, is the lowest. By analysing the MC for defender, the MC was Malaysian Ringgit 825,000 at year 6. The MC of defender is bigger than min EUAC of challenger at year 6. Hence, replacement should be made by end of year 6.

Table-4. Modified marginal cost for defender.

(1) End of Year *k*	(2) MV, End of Year *k*	(3) Loss in Market Value (MV) during Year *k*	(4) Cost of Capital = 10% of Beginning of Year MV	(5) Annual Expenses (*Ek*)	(6) Yearly Cost due to maintenance (Cy)	(7) Loss of Opportunity (Lo)	(8) [=(3) + (4) + (5) + (6) + (7)] Marginal Cost for Year (TC*k*)
0	150,000	-	-	-	-	-	-
1	135,000	15,000	15000	16800	10,000	675,000	731,800
2	120,000	15,000	13500	16800	15,000	675,000	735,300
3	105,000	15,000	12000	16800	20,000	712,500	776,300
4	90,000	15,000	10500	16800	25,000	675,000	742,300
5	75,000	15,000	9000	16800	30,000	675,000	745,800
6	65,000	10,000	7500	16800	35,000	825,000	894,300
7	55,000	10,000	6500	16800	40,000	900,000	973,300
8	45,000	10,000	5500	16800	45,000	712,500	789,800
9	35,000	10,000	4500	16800	50,000	750,000	831,300
10	25,000	10,000	3500	16800	55,000	750,000	835,300

Table-5. Modified marginal cost and EUAC for challenger.

(1) End of Year *k*	(2) MV, End of Year *k*	(3) Loss in Market Value (MV) during Year *k*	(4) Cost of Capital = *i*% of Beginning of Year MV	(5) Annual Expenses (*Ek*)	(6) Yearly Cost due to maintenance (Cy)	(7) Loss of Opportunity (Lo)	(8) [=(3) + (4) + (5) + (6) + (7)] Marginal Cost for Year (TC*k*)	(7) EUAC through Year *k*
0	400,000	-	-	-	-	-	-	-
1	370,000	30,000	40000	16,800	10,000	675,000	771,800	771808
2	350,000	20,000	37000	16,800	15,000	675,000	763,800	767987
3	335,000	15,000	35000	16,800	20,000	675,000	761,800	766076
4	320,000	15,000	33500	16,800	25,000	675,000	765,300	765999 min
5	305,000	15,000	32000	16,800	30,000	675,000	768,800	766401

CONCLUSION

The proposed model on replacement incorporated both the technical and economic criteria. The incorporation of these critical failures covers the commercial requirement of the industry. Hence, the model could be useful for the industry to make a decision on the robot replacement. In most cases, the probability of failures of robots in the top coat system were mainly due to servo motor with 0.20 probability of failure. The third robot which was having the lowest MTBF value 5280 hours was candidate for replacement. Based on the case study, the cost of maintaining defender at year 6 was Malaysian Ringgit 825,000, while the minimum cost of annual operating of challenger was Malaysian Ringgit 765,999. It is noted that the cost of the maintaining the defender was higher than the minimum annual operating cost of challenger at year 6. Hence, replacement of defender should be made by end of year 5.

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