

Automated platform for designing multiple robot work cells

N S Osman^{*1}, M A A Rahman^{1*}, A A Abdul Rahman¹, S H Kamsani¹, B M Bali Mohamad¹, E Mohamad¹, Z A Zaini², M F Ab Rahman² and M N H Mohamad Hatta¹

¹Integrated Manufacturing System (I'Ms), Advanced Manufacturing Centre (AMC), Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Melaka, Malaysia.

²Department of Occupational Safety and Health, Aras 2, 3 & 4, Blok D3, Kompleks D, Pusat Pentadbiran Kerajaan Persekutuan, 62530 W. P. Putrajaya, Malaysia.

E-mail: *norsuriyanti@gmail.com

Abstract. Designing the multiple robot work cells is very knowledge-intensive, intricate, and time-consuming process. This paper elaborates the development process of a computer-aided design program for generating the multiple robot work cells which offer a user-friendly interface. The primary purpose of this work is to provide a fast and easy platform for less cost and human involvement with minimum trial and errors adjustments. The automated platform is constructed based on the variant-shaped configuration concept with its mathematical model. A robot work cell layout, system components, and construction procedure of the automated platform are discussed in this paper where integration of these items will be able to automatically provide the optimum robot work cell design according to the information set by the user. This system is implemented on top of CATIA V5 software and utilises its Part Design, Assembly Design, and Macro tool. The current outcomes of this work provide a basis for future investigation in developing a flexible configuration system for the multiple robot work cells.

1. Introduction

Rapid development of various industrial technologies has stimulated a substantial increase in the use of industrial robot [1]. It is proved through the latest statistic presented by the International Federation of Robotics (IFR) in its 2015 World Robotics report, the utilization of industrial robot in manufacturing industry is shown to be increasing from 2013 to 2017. Also, it is predicted that by 2018, global sales of industrial robots will grow on average by at least 15% yearly [2]. Few researchers claim that industrial robot is used extensively in application such as welding, drilling, assembly, transportation, cutting, spraying, measuring, stacking, and laser processing [3]–[5]. Consequent from the report and claim, configuration work of robot work cell become an intensive challenge among the design engineers in ensuring the developed robot work cell effectively in actual production. Based on the common configuration approach, configuring work requires a high investment cost [6], long commissioning time, high level of expert knowledge and lots of human involvement [1], [7], [8]. Additionally, configuration work is tricky to implement as it needs to



account about the safety element [9], [10]. Hence, this work proposes an automated configuration platform of multiple robot work cells, where aiming to provide fast and easy configuration work with minimum cost, human involvement and certain investments such as the trial and error adjustment.

Previous work introduced in [9] on the design safety measure robot work cell are taken into consideration for this work. The illustration of two-dimensional (2D) robot work cell with its safety measure as depict in figure1 is used to model the safety multi-robot work cells.

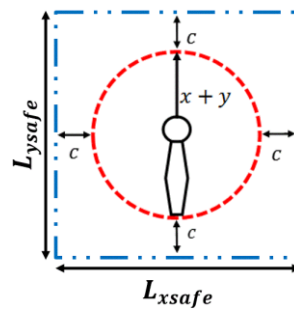


Figure 1. Illustration of 2D Robot Work Cell with Safety Clearance

$$\begin{aligned} A_{safe} &= L_{xsafe} \times L_{ysafe} \\ &= 2(X + Y + C) \times 2(X + Y + C) \end{aligned} \quad (1)$$

Where,

X: Length of robot arm (mm)

Y: Length of the robot tooling and work piece (mm)

C: Clearance for the worker movement in a work cell taken as 650mm

A concept of variant-shaped configuration introduced in [11], [12] are taken as reference. This concept involves a maximum of ten industrial robots where only two auxiliary equipment are considered which are the robot tooling and the work piece. The variant-shaped configuration was established by joining one or more square robot work cell (figure 1) side by side according to the quantity of robot used. The configuration concept emphasizes only on the simple arrangement. Meanwhile, the complex arrangement is excluded in this work due to the difficulty in tracking the configuration trend. The complex arrangement refers to the corner, half facing, diagonal and mix arrangement. Additionally, this configuration concept excludes the rigid transformation condition such as translation, rotation, reflection or glide reflection. As the results, the data of possible layout of the variant-shaped configuration is presented as shown in table 1. This is the key element to the invention of the next stage.

Table 1. Variant-Shaped Robot Work Cell Configuration Data

Number of Robot, Nr	1	2	3	4	5	6	7	8	9	10
Number of Configuration, Nc	1	1	2	5	12	35	108	369	1285	4655

Afterwards, an optimization concept of configuration work in [11] is utilized. In this work, the earlier variant-shaped configuration (data, pattern and equation) was optimized by grouping the number of configuration into the columns configuration based on the same total number of robot in the references line at the horizontal plane. The columns configuration must avoid the rigid transformation and the diversity position. Diversity position refers to the layout or configuration which have the same number of robot in every horizontal line but different in position where they can be considered as a same layout. At this stage, the configuration data, pattern and equation have been

optimized and the complexity have been reduced. table 2 presents the optimal robot work cell configuration data.

By using the previous concept, the mathematical models of each optimal configuration was developed and the rule of optimal selection was modelled in this work where it provides a framework to create the GUI later on. Few studies [13]–[20] has proved that CATIA is widely used in creating an automatic and intelligent system which able to enhance the development time, minimize the errors and could introduce technologies faster to the market [17], [18]. Therefore, CATIA 3D models, Visual Basic (VB) Interface and macro tools were selected for developing a completed GUI for the automated platform.

Table 2. Optimal Robot Work Cell Configuration Data

Number of Robot, Nr	1	2	3	4	5	6	7	8	9	10
Number of Optimal Configuration, No.c	1	1	2	3	4	6	8	12	16	22

The developed automatic platform may provide the simulation of the robot work cell configuration before the real configuration work where an optimal robot work cell layout was proposed and the workspace area, W_A and manufacturing throughput time, MTT of the robot work cell layout were calculated and presented. The consequence of this work will enhance the current approach of configuring the robot work cell. Also, it could intensify the human-robot interaction as well as alleviate the configuration cost and time in future.

2. Related Works

Configuration work here refers to the laying out the robot work cell according to the manufacturing strategy set by the certain industry. Most of the configuration studies aim to propose a quality configuration approach where it would be very advantageous to the design engineers in handling the configuration work later on. For example, a study in [14] presented the optimal placement for the described duties within the robotic manipulator workspace. This work utilized the response surface approach for the both path translation and rotation. Based on the approach, a robotic optimisation tool as the add-in to the RobotStudio has been developed. The approach was verified properly by optimising the positioning of the industrial robots with its path in 4 varies showcases for attaining a minimal cycle time. Despite, this study only focused on single robot, whereas in the actual application, one or many robots could be present in the work cell. Another study in [15] introduced an optimisation work for laying out multi-robot work cells in a vertical section plane where emphasis to manufacture the outer surface of a large fuselage panel. This work intends to maximise the overlapped workspace among two robots without collision between both robots and work pieces. This work capable to achieve a layout that yielded reasonable positions by tested on an existing layout. Anyhow, this work can only be used for two robot only.

Afterwards, a study in [16] provides a system with its method for optimising of the position of the different workstations in the industrial robot work cell. The developed system and its method involve one or many tasks and the industrial robot for carrying out these tasks. This work intends to enhance the performance of the robot as well as enhance the productivity of the robotic work cell. Nonetheless, the study was not applicable in the cases which used more than one robots. Additionally, an innovative layout approach by [17] was promoted. The developed approach is based on the Differential Evolution (DE) where it is utilized for solving the Facility Layout Planning (FLP). Robotic work cell layout was one FLP example that was described in this work. The mathematical FLP model includes few constraints and optimisation objective was proposed and an automated layout optimisation was

developed for accomplishing the 3-D visualisation demonstration for the optimal layout. Yet, this work requires highly skilled and experienced worker for understanding the approach.

Besides, an optimal robot positioning for tasks execution was introduced in [2]. This work aims to optimise the base position of an industrial robot to reach all predefined tasks as well as minimise the cycle time. Apart from that, this work integrated the robot inverse kinematics and collision avoidance with a derivative-free optimisation algorithm. The outcomes of this work had successfully provided a feasible solution in enhancing the cycle time for a robot station by placing the robot in optimal position. However, future work would be focused on the optimization of the placements for several robots, and on the automatic creation of the optimization approach.

The previous studies depicts that various configuration approach was proposed, yet there are still needs in enhancing the current configuration work. Thus, this work aims to settle the raised issue through modelling mathematical models of each optimal robot work cells and the rule of optimal selection where it is the framework of the automated platform in identifying the final optimum layout of robot work cell. The proposed automated platform could simplify the configuration work later on and lessen the configuration cost, time, human involvement with low future investment and as well as satisfy the user necessities.

3. Development Process of the Automated Configuration Platform

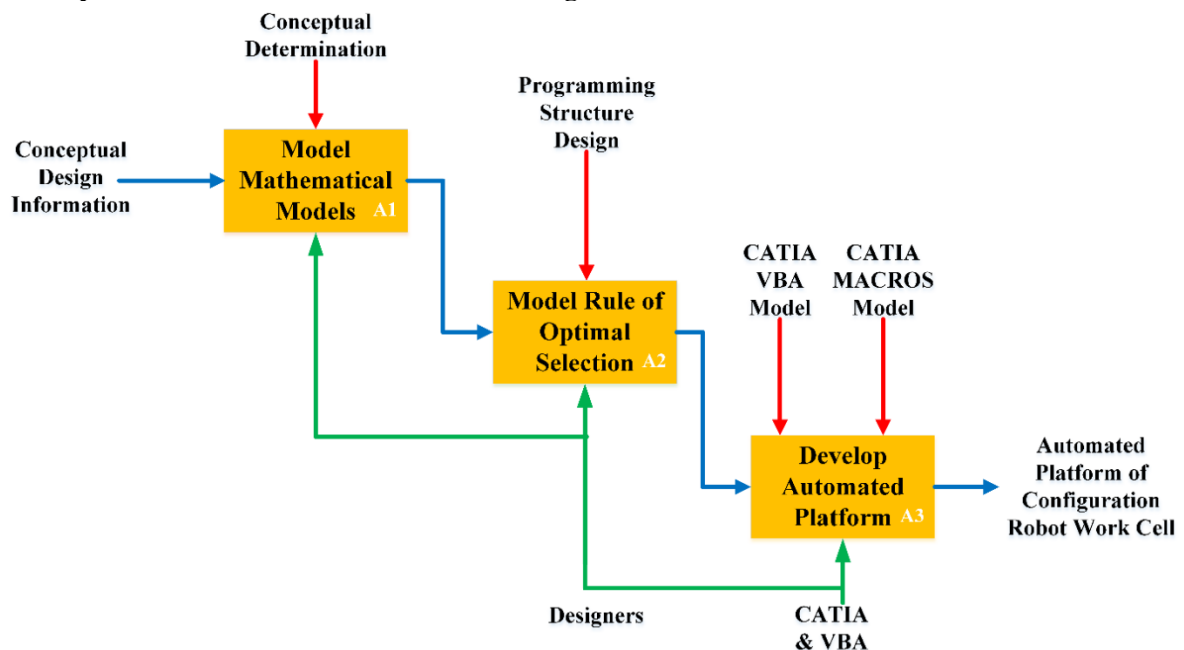


Figure 2. Development Process of the Automated Configuration Platform

Development of the automated configuration platform begins with the determination of previous configuration concept where the probable optimal robot work cells were identified. Later, the mathematical models such as workspace area, A_W and manufacturing throughput time, MTT were derived for each of the probable optimal robot work cell. Next, the rule of optimal selection was modelled in the form of forward chain which it is the framework of the automated configuration platform. Lastly, a completed GUI is generated by using the CATIA VBA and macro. Three levels of user form will be designed where each of the level will running their own specific tasks. The completed GUI of the automated configuration platform is verified by executing a set of user data based on the selection of configuration types (normal configuration, configuration with minimum

workspace area, configuration with minimum throughput time and configuration with both minimum workspace area and throughput time). The outcomes of the verification is presented and discussed through this activity.

4. Result and Discussion

4.1 Probable Optimal Robot Work Cell with its Mathematical Models

As the results, 22 probable optimal robot work cell layouts have been finalized for 10 number of robots. Three probable optimal robot work cell configurations were selected to represent the outcome of this work where the workspace are, A_w and the manufacturing throughput time, MTT were derived for each of the configuration. Both workspace area, A_w and manufacturing throughput time, MTT equations were modelled based on the basis equations introduced in [21].

4.1.1 Configuration 1

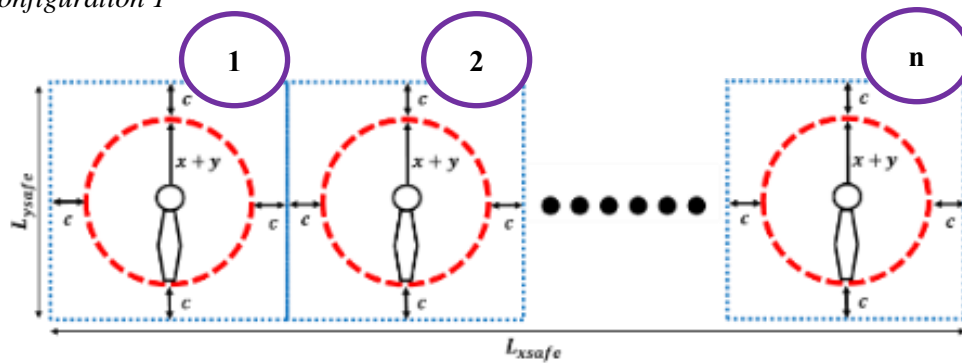


Figure 3. Robot Work Cell Configuration 1

I. Workspace Area, A_w

$$A_w = L_{safe} \times W_{safe}$$

$$W_{safe} = 2 \max_{1 \leq n \leq 10} [x_n + y_n + c]$$

$$L_{safe} = 2 \sum_{i=1}^n [(x_i + y_i) + nc]$$

II. Manufacturing Throughput Time, MTT

$$MTT = \sum_{i=1}^n (t_p + t_i + t_m + t_q)_i$$

4.1.2 *Configuration 2* The manufacturing throughput time for this configuration will be diverse from the configuration 1 where for robot 1 and robot 2, only the maximum manufacturing throughput time will be selected to be sum up with the rest of robot's manufacturing throughput time.

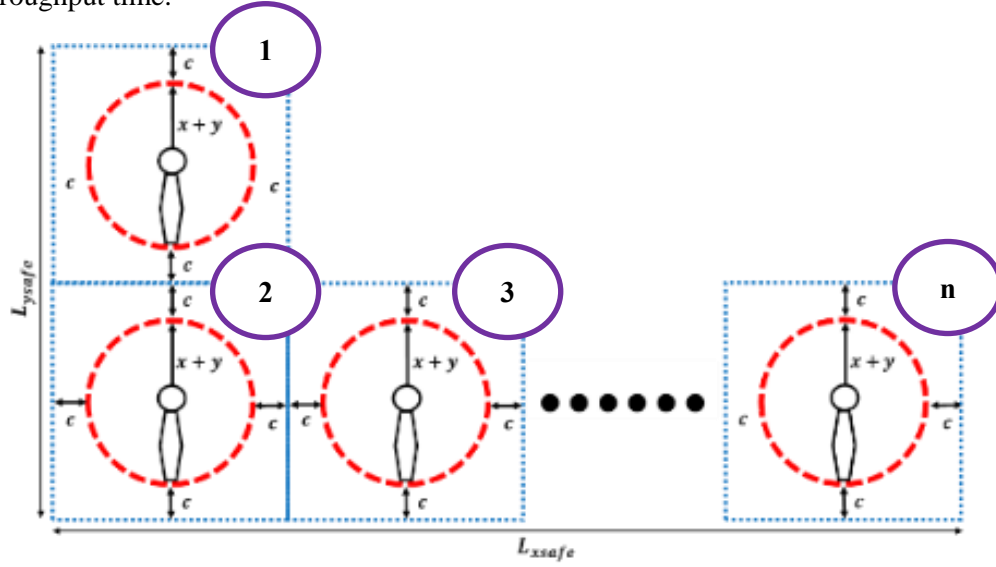


Figure 4. Robot Work Cell Configuration 2

I. Workspace Area, A_w

$$A_w = L_{safe} \times W_{safe}$$

$$L_{safe} = 2 \sum_{i=2}^n [(x_i + y_i) + (n-1)c]$$

Or

$$= 2[(x_1 + y_1) + c]$$

$$W_{safe} = 2 \sum_{i=1}^2 [(x_i + y_i) + 2c]$$

Or

$$= \max_{3 \leq n \leq 10} 2[(x_n + y_n) + c]$$

II. Manufacturing Throughput Time, MTT

$$MTT = \max \sum_{i=1}^2 (t_p + t_i + t_m + t_q)_i + \sum_{i=3}^n (t_p + t_i + t_m + t_q)_i$$

4.1.3 *Configuration 3* The manufacturing throughput time for this configuration is the summation of maximum manufacturing throughput time for robot 1 and robot 3 with maximum manufacturing throughput time between robot 3 and robot 4 and the rest of robot's manufacturing throughput time.

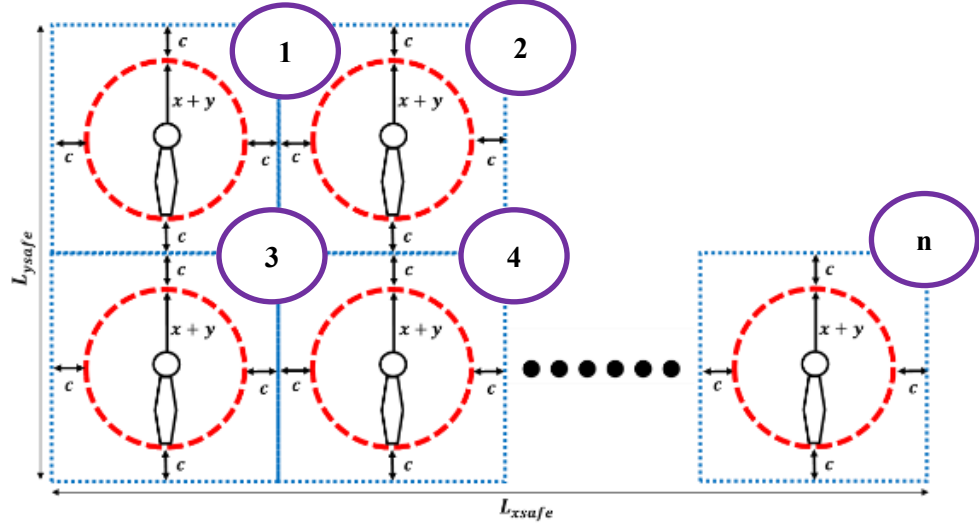


Figure 5. Robot Work Cell Configuration 3

I. Workspace Area, A_w

$$A_w = L_{safe} \times W_{safe}$$

$$L_{safe} = 2 \sum_{i=3}^n [(x_i + y_i) + (n-2)c]$$

Or

$$= 2 \sum_{i=1}^2 [(x_i + y_i) + 2c]$$

$$W_{safe} = 2 \sum_{n=1,3} [(x_n + y_n) + 2c]$$

Or

$$= 2 \sum_{n=2,4} [(x_n + y_n) + 2c]$$

Or

$$= \max_{5 \leq n \leq 10} 2[(x_n + y_n) + c]$$

II. Manufacturing Throughput Time, MTT

$$MTT = \max \sum_{i=1,3} (t_p + t_i + t_m + t_q)_i + \max \sum_{i=2,4} (t_p + t_i + t_m + t_q)_i + \sum_{i=5}^n (t_p + t_i + t_m + t_q)_i$$

4.2 Rule of Optimal Selection of the Automated Configuration Platform

Figure 6 presents the forward chain of the optimal selection of the robot work cell for up to three number of robots. Basically, 11 forward chains and rules were developed in this work where only 3 forward chains were selected represent the outcome where it is used as a data driven method of deriving a particular goal from a given knowledge base with a set of inference rules.

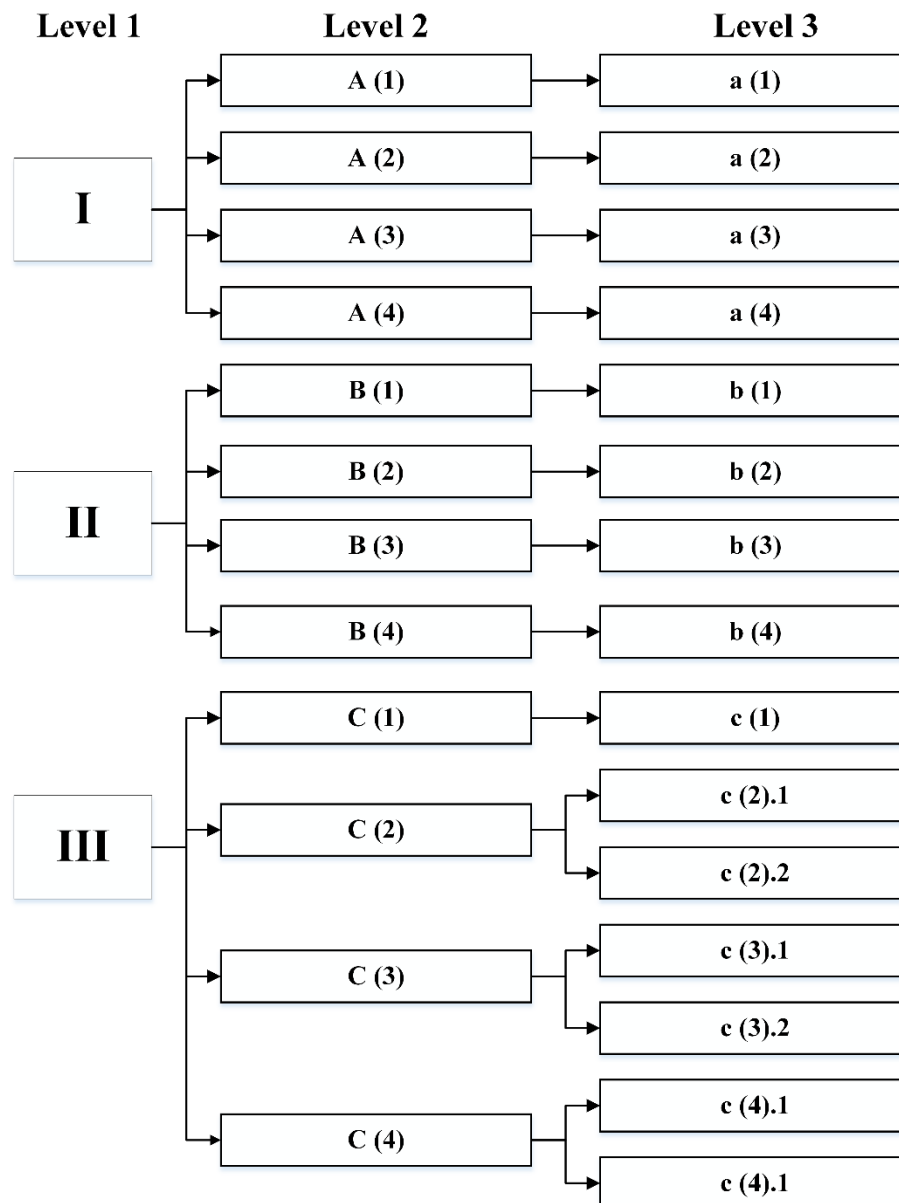


Figure 6. Forward Chain of the Automated Configuration Platform

Basically there are three level of the forward chains which are:

Level 1

I = 1 Robot

II = 2 Robots

III = 3 Robots

Level 2

A(1) / B (1) / C(1) = Normal Configuration

A(2) / B(2) / C(2) = Configuration with Minimum Workspace Area

A(3) / B(3) / C(3) = Configuration with Minimum Manufacturing Throughput Time

A(4) / B(4) / C(4) = Configuration with both Minimum Workspace Area and Manufacturing Throughput Time

Level 3

a(1) / b (1) / c(1).1 = Normal Configuration with Robot Work Cell 1

a(2) / b(2) / c(2).1 = Configuration with Minimum Workspace Area with Robot Work Cell 1

c(2).2 = Configuration with Minimum Workspace Area with Robot Work Cell 2

a(3) / b(3) / c(3).1 = Configuration with Minimum Manufacturing Throughput Time with Robot Work Cell 1

c(3).2 = Configuration with Minimum Manufacturing Throughput Time with Robot Work Cell 2

a(4) / b(4) / c(4).1 = Configuration with both Minimum Workspace Area and Manufacturing Throughput Time with Robot Work Cell 1

c(4).2 = Configuration with both Minimum Workspace Area and Manufacturing Throughput Time with Robot Work Cell 2

For the inference rule, 4 rules elaborated in this paper as shown in table 3. Rule 0 is utilized for identifying the rule number based on the selection of robot quantity. Meanwhile, Rule 1, Rule 2 and Rule 3 were used to determine the final optimal robot work cell with its workspace area and manufacturing throughput time calculation for 1 robot, 2 robots and 3 robots respectively.

Table 3. Inference Rule of Optimal Selection of Robot Work Cell Configuration

Rule 0	Rule 1	Rule 2	Rule 3
If 1 Then Rule 1	If 1 & A(1) Then a(1)	If 2 & B(1) Then b(1)	If 3 & C(1) & c(1).1 Then c(1).1
If 2 Then Rule 2	If 1 & A(2) Then a(2)	If 2 & B(2) Then b(2)	If 3 & C(1) & c(1).2 Then c(1).2
If 3 Then Rule 3	If 1 & A(3) Then a(3)	If 2 & B(3) Then b(3)	If 3 & C(2) & c(2).1 Then c(2).1

If 4 Then Rule 4	If 1 & A(4) Then a(4)	If 2 & B(4) Then b(4)	If 3 & C(2) & c(2).2 Then c(2).2
If 5 Then Rule 5			If 3 & C(3) & c(3).1 Then c(3).1
If 6 Then Rule 6			If 3 & C(3) & c(3).2 Then c(3).2
If 7 Then Rule 7			If 3 & C(4) & c(4).1 Then c(4).1
If 8 Then Rule 8			If 3 & C(4) & c(4).2 Then c(4).2
If 9 Then Rule 9			
If 10 Then Rule 10			

4.3 Automated Configuration Platform of Robot Work Cell

A GUI of the automated configuration platform is invented wherein it comprises of three different levels of user interface. First level user interface is used to begin the configuration process. User is asked to select the “Number of Robot” based on the quantity of robot used and once user click the “Start” button, the next level of user interface will appear automatically. (Refer figure 7).

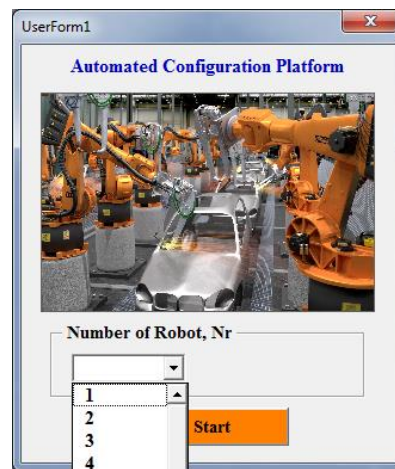


Figure 7. First Level User Interface

Next level user interface (figure 8) is utilized to calculate the workspace area, A_w and manufacturing throughput time, MTT and identified the optimal robot work cell based on the configuration type selection. In this level, user need to input the robot information such as the robot arm length (mm) and the robot tooling and work piece length (mm). Also, the manufacturing throughput time data such as the inspection time, t_i , process time, t_p , move time, t_m and queue time, t_q .

Figure 8. Second Level User Interface

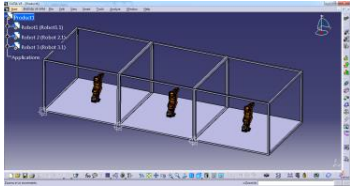


Finally, the last level user interface as in figure 9 is presented where the final robot workspace area, A_W and manufacturing throughput time, MTT with the proposed optimal layout are displayed.

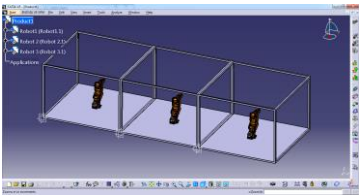
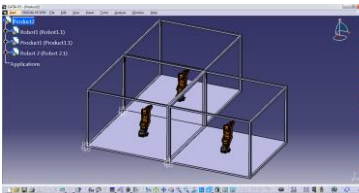
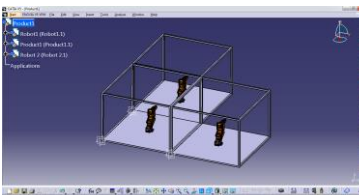
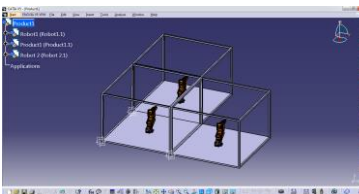
Figure 9. Third Level User Interface

4.4 Verification of the Automated Configuration Platform

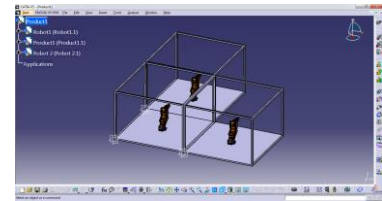
For the verification activity, 3 number of robots and a set of robot and manufacturing throughput time data with various configuration types are run to present the result of the developed GUI as shown in the table 4.

Table 4. Verification Result of the Automated Configuration Platform of Robot Work Cell

Robot 1 Data	Robot 2 Data	Robot 3 Data	Configuration Types	Workspace Area (mm) & Manufacturing Throughput Time (sec)	Proposed Optimal Robot Work Cell
$x = 100$	$x = 100$	$x = 100$	Normal Configuration	$L_{safe} = 5100$	
$y = 100$	$y = 100$	$y = 100$		$W_{safe} = 1700$	
$t_i = 10$	$t_i = 10$	$t_i = 10$		$MTT = 120$	
$t_p = 10$	$t_p = 10$	$t_p = 10$			
$t_m = 10$	$t_m = 10$	$t_m = 10$			
$t_q = 10$	$t_q = 10$	$t_q = 10$			
$x = 100$	$x = 200$	$x = 300$	Normal Configuration	$L_{safe} = 5400$	
$y = 25$	$y = 50$	$y = 75$		$W_{safe} = 2050$	
$t_i = 10$	$t_i = 20$	$t_i = 10$		$MTT = 155$	
$t_p = 10$	$t_p = 10$	$t_p = 20$			
$t_m = 10$	$t_m = 30$	$t_m = 10$			
$t_q = 10$	$t_q = 10$	$t_q = 5$			
$x = 100$	$x = 100$	$x = 100$	Configuration with Minimum Workspace Area	$L_{safe} = 5100$	
$y = 100$	$y = 100$	$y = 100$		$W_{safe} = 1700$	
$t_i = 10$	$t_i = 10$	$t_i = 10$		$MTT = 120$	
$t_p = 10$	$t_p = 10$	$t_p = 10$			
$t_m = 10$	$t_m = 10$	$t_m = 10$			
$t_q = 10$	$t_q = 10$	$t_q = 10$			

$x = 100$	$x = 200$	$x = 300$	Configuration with Minimum Workspace Area	$L_{safe} = 5400$	
$y = 25$	$y = 50$	$y = 75$		$W_{safe} = 2050$	
$t_i = 10$	$t_i = 20$	$t_i = 10$		$MTT = 155$	
$t_p = 10$	$t_p = 10$	$t_p = 20$			
$t_m = 10$	$t_m = 30$	$t_m = 10$			
$t_q = 10$	$t_q = 10$	$t_q = 5$			
$x = 100$	$x = 100$	$x = 100$	Configuration with Minimum Manufacturing Throughput Time	$L_{safe} = 3400$	
$y = 100$	$y = 100$	$y = 100$		$W_{safe} = 3400$	
$t_i = 10$	$t_i = 10$	$t_i = 10$		$MTT = 80$	
$t_p = 10$	$t_p = 10$	$t_p = 10$			
$t_m = 10$	$t_m = 10$	$t_m = 10$			
$t_q = 10$	$t_q = 10$	$t_q = 10$			
$x = 100$	$x = 200$	$x = 300$	Configuration with Minimum Manufacturing Throughput Time	$L_{safe} = 3850$	
$y = 25$	$y = 50$	$y = 75$		$W_{safe} = 3350$	
$t_i = 10$	$t_i = 20$	$t_i = 10$		$MTT = 115$	
$t_p = 10$	$t_p = 10$	$t_p = 20$			
$t_m = 10$	$t_m = 30$	$t_m = 10$			
$t_q = 10$	$t_q = 10$	$t_q = 5$			
$x = 100$	$x = 100$	$x = 100$	Configuration with both Minimum Workspace Area and Manufacturing Throughput Time	$L_{safe} = 3400$	
$y = 100$	$y = 100$	$y = 100$		$W_{safe} = 3400$	
$t_i = 10$	$t_i = 10$	$t_i = 10$		$MTT = 80$	
$t_p = 10$	$t_p = 10$	$t_p = 10$			
$t_m = 10$	$t_m = 10$	$t_m = 10$			
$t_q = 10$	$t_q = 10$	$t_q = 10$			

$x = 100$	$x = 200$	$x = 300$	Configuration with both Minimum Workspace Area and Manufacturing Throughput Time	$L_{safe} = 3850$
$y = 25$	$y = 50$	$y = 75$		$W_{safe} = 3350$
$t_i = 10$	$t_i = 20$	$t_i = 10$		$MTT = 115$
$t_p = 10$	$t_p = 10$	$t_p = 20$		
$t_m = 10$	$t_m = 30$	$t_m = 10$		
$t_q = 10$	$t_q = 10$	$t_q = 5$		



5. Conclusion

An automated configuration platform has been proposed where the configuration concept, mathematical models with its GUI are elaborated in this paper. The essential purpose of this work was providing a better understanding in the designing and developing of the configuration system. Additionally, this work plans to provide a fast and simple platform for design engineers with the present of the significant data in regards to the robot work cell configuration system. Future work will focus on the improvement of the configuration platform which includes other complex user requirements.

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