

PERFORMANCE MODELLING OF RECONFIGURABLE ASSEMBLY LINE

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Abstract

This paper deals with the modelling and simulated performance analysis of a reconfigurable assembly line (RAL). The RAL model considered in this work has a set of in-line movable robots, which can move on a guided path to serve various workstations. Each robot in the RAL can access and serve more than one workstation by moving to their locations while satisfying the accessibility constraints. Capacity flexibility is addressed by varying the number of serving robots in the system. Error recovery flexibility is addressed by pulling out the failed robot from the assembly line for repair. The failed robot is reintroduced into assembly line after its repair. The system hardware has plug and play capabilities for ease of handling of system resources. Assumptions are made to simplify the problem as well as to highlight the specific features considered in the model. Simulation results have been presented to show the effectiveness of the proposed model.

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Key Words: Reconfigurable Assembly Line (RAL), Modelling and Simulation, Performance Analysis

1. INTRODUCTION

The increasing demands for productivity, cost reduction, and optimal allocation of resources, have motivated continuous research in modelling and performance evaluation of manufacturing systems. In this domain, one of the most important manufacturing sections is assembly line system. Due to technological advances, most of the present day assembly systems are automated. The automation in assembly lines is motivated by the advances in the field of robotics. Industrial robots are permanent features in most of the automated assembly systems. Automated assembly systems involve a significant investment due to automated equipments such as part feeding devices, part holding devices, and robots. As assembly operations do not have the large mechanical force and power requirements for processing operations, the utilization of robots plays major role on the cost of the assembled products.

Automated assembly system performs a sequence of assembly operations to combine multiple components into a single product. The single product can be a final product or a subassembly in a larger product. In general, the assembled entity consists of base part to which other components are attached. There are a huge number of applications of assembly system. However, some of the important applications that require robots are electronics assembly such as printed circuit boards, and mechanical component assembly.

A typical automated assembly system consists of the following subsystems: (1) one or more workstations at which the assembly steps are accomplished, (2) parts feeding devices that deliver the individual components to the workstations, and (3) a work handling system for assembled entity. Automated Assembly systems can be classified based on the physical configurations as (a) in-line assembly system or assembly line, (b) dial-type machine, (c)

carousel assembly system, and (d) single station assembly machine. In this work, attention is given to automated assembly line which can be reconfigurable to cope up with the demand fluctuations and resource failures, thus, called reconfigurable assembly line (RAL).

During a product's life cycle, the demand for the product is low in the beginning. Afterwards, it increases as the product reaches its maturity stage. Product demand may decrease again due to the introduction of newer and better products in the market place. Along with product specific fluctuations, demand of the product may also fluctuate due to market disturbances. To respond to such turbulences, assembly lines must have capacity flexibility. In addition, they should possess error recovery flexibility to deal with internal disturbances during its operation.

In general, conventional assembly lines are designed to meet maximum demand during product life cycle, which incurs high overheads in the form of idle resources during initial and declining stages of product life cycle. This results in under utilization of system resources and results in high production cost. Thus, reconfigurable/adaptive assembly lines are needed to handle varying product demands and internal disturbances.

In many cases, automated assembly lines consist of several workstations having random or deterministic operation, failure, and repair times. For such systems, discrete event simulation seems to be the best way of analyzing the system. In this work, a model of a RAL has been proposed in which a set of movable robots serve workstations. Behaviour of the taken model is studied to improve its performance. Simultaneously, the effect of varying the number of robots according to product demand during product life cycle and internal disturbances are also studied. This work has been motivated from the Adaptive Production Systems that are in use at Denso Corporation, Japan.

2. LITERATURE REVIEW

Modelling, analysis, and implementation of reconfigurable manufacturing systems focus on various aspects, such as rapid change in the system configuration, their machines, and controls, in order to quickly adjust production capacity and functionality in response to sudden market changes. During the last few years, two technologies that are necessary enablers for reconfiguration have emerged: in software, modular, open-architecture controls that aim at allowing reconfiguration of the controller [1]; and in machine hardware, modular machine tools that aim at offering the customer more machine options [2, 3]. Landers [4] reported a new paradigm in machine tools and controllers with modular and reconfigurable features. Valerie & Hu [5] used AHP (Analytic Hierarchy Process) to select an optimum configuration based on reconfigurable performances. Asl et al., [6] proposed a dynamic modelling and stability analysis by comparing an RMS with an equivalent fluid system. Kalita & Khargonekar [7] presented a hierarchical structure and framework for the modelling, specification, analysis and design of logic controllers for a reconfigurable manufacturing system. Ying & Zhou [8] proposed a heuristic algorithm for the design of a reconfigurable semiconductor manufacturing system. Xiaobo et al., [9, 10, 11, 12] developed and reported a stochastic model of RMS in four parts; a framework, optimal configurations, optimal selection policy, and performance measure. Abdi & Labib [13] reported a case study on design strategy for RMS using analytical hierarchical process (AHP). They divided the design stage into strategic and tactical levels and discussing the strategic level, a link between market and manufacturing is established to group products into families. Savsar [14] developed a simulation model for an electronic assembly line, which deals with weekly scheduled demands for printed circuit boards.

The considered model can accommodate change in demand of product by employing varying number of robots required for assemblage. The process of increasing the degree of

automation or to add new modules to the existing system take some time, where the proposed model can accommodate the change in production rate very quickly. Simply adding and removing robots required for assemblage on the guided path can change production capacity of the RAL in no time.

3. MODEL DESCRIPTION

Assembly, such as electronics assembly, involves mounting of several components on a main body. Several steps have to be carried out in the assembly process. These steps have precedence relationship because of technology and other constraints. To reduce the lead time of assembly operation, these steps are grouped into several stages. Number of stages and operation times at each stage are arranged in such a way that the assembly line is fully balanced. The current state of technology in the field of automated assembly lines covers only dedicated assembly lines, where stationary robots serve the workstations. In such systems, robot failures affect the system output. With the failure of any robot entire assembly line stops production until the failed robot is repaired.

In the proposed RAL model, a set of movable robots (in-line robots) serve a series of workstations, while moving along a guided path. If a robot breaks down, it is pulled out of the line for repair, with remaining robots performing their work without much delay. Each workstation can have different operational (i.e. assembling) time and hence different production rate. A suitable buffer space is provided in between workstations for the storage of semi-assembled parts. It is assumed that base part enters from one end (i.e. from an external source) and various sub components are added to the main body of the base part at successive workstations to complete the final assembly. Base part moves on a conveyor from one workstation to another. Assemblage of parts is based on first come first served (FCFS) principle. Several assumptions, such as, base part arrivals follow exponential distribution; assembly times at each station are known in advance and are deterministic; robot failures follow uniform distribution and robot repairs take fixed times, are made in the present study. Another assumption is, transportation time of part between a pair of workstations is either neglected or included in the operation times at the workstations. A simulation program has been developed using C language, to imitate the behaviour of the proposed system. The simulation program works for different number of workstations with variable number of robots. However, for the sake of explanation a case study consisting of six workstations, four in-line robots, and one supervisory robot is considered. A schematic view of the RAL with the six workstations and four robots is shown in Fig.1. Intermediate buffers between workstations are defined by a buffer vector $B = (B_1, B_2, B_3, B_4, B_5, B_6)$. The buffer size at first workstation is taken as infinite (i.e. $B_1 = \infty$) for the purpose of analysis.

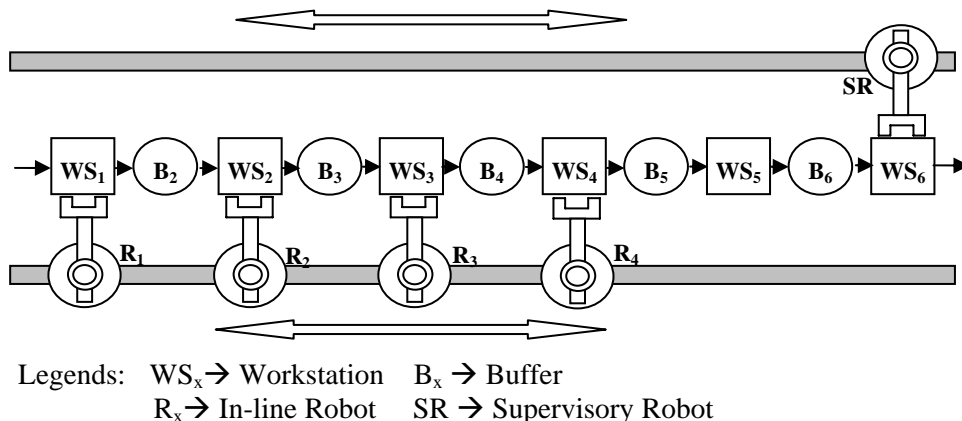


Figure 1: Reconfigurable assembly line.

Initially all robots are positioned in-line starting from WS₁ to WS₄ and supervisory robot is placed at the last WS (i.e., WS₆) on the opposite side of the in-line robots. Supervisory robot is the robot, which can serve all WSs as it is only robot on the guided path opposite to in-line robots. Due to the constraint of guided path, each of the in-line robots can serve only a few accessible workstations. It is important to mention that one robot can serve only one workstation at a time and robots can not crossover each other. An accessibility constraints table for the robots is generated automatically by using a simple reasoning. If N is the number of workstations and M is number of in-line robots in the assembly line then i^{th} robot (R_i) can serve only from WS _{i} to WS _{$(N-M+i)$} workstations. However, as supervisory robot is situated on the other side of the guided path it can serve all workstations (i.e. from WS₁ to WS _{N}).

Table I summarizes accessibility constraints of each robot for the considered assembly line. In this table, ‘1’ indicates the accessibility of workstation WS _{x} to robot R _{x} , while ‘0’ represents its non-accessibility.

Table I: Robot accessibility constraints.

$R_x \backslash WS_x$	WS ₁	WS ₂	WS ₃	WS ₄	WS ₅	WS ₆
R ₁	1	1	1	0	0	0
R ₂	0	1	1	1	0	0
R ₃	0	0	1	1	1	0
R ₄	0	0	0	1	1	1
SR	1	1	1	1	1	1

3.1 Working of RAL model

After arrival of the base part at buffer B₁, system controller puts it in queue according to FCFS basis. If WS₁ is free at that time and no other part is waiting in the queue then part will be loaded on to WS₁ directly. Subsequently, controller searches for a nearest, accessible and free robot for WS₁ to perform the required assembly operation. If there is a free and accessible robot, then controller dispatches it to the requesting workstation. If there is more than one choice, then controller dispatches the nearest robot to the workstation. After reaching the workstation, robot requests for an appropriate program to execute the sequence of steps at that station. Selection of the program is made after checking the current workstation of the requesting robot. After performing the intended operation at the workstation, robot waits for the next call. If free and accessible robot is not available for dispatch to the calling workstation, workstation is kept on waiting list. This process is repeated until all operations on the incoming part are completed. Finally, part departs the assembly line from the last workstation.

4. PERFORMANCE ANALYSIS OF RAL

During the life cycle of RAL, decision-making is involved at various stages of design, planning, and operation. The role of performance analysis is to aid this decision-making in an effective way. Finding the effect of adding or withdrawing resources (i.e. robots), sudden changes in demand for a product and robot failure can be studied with the help of performance analysis. Performance analysis can be done using analytical and discrete event simulation approaches.

Analytical modelling is not flexible and needs too many assumptions, which makes it not suitable for this type of systems. However, rough estimation can be made using analytical models. For instance, theoretical production rate (R_c) of the assembly line can be calculated as $R_c = 1/T_c$, and $T_c = T_{tr} + T_{bo}$; where T_c = cycle time, T_{tr} = transfer time between successive

workstations, and T_{bo} = maximum operation time among all workstations i.e. bottleneck operation time. Production rate of each station is different and is inversely proportional to its operation time. The ratio of actual production to the maximum possible production at each workstation gives theoretical utilization of that workstation. Actual rate of production can be calculated by considering the availability of the resources at the workstation.

From WS_1 to WS_6 , time units 5 – 8 – 4 – 9 – 4 – 5, are considered as operational times respectively for the proposed model. The mean of exponentially distributed part inter-arrival time is considered as 6 time units. For the data considered above, the maximum rate of production possible, neglecting transfer time between stations, is 1/9 (i.e. 0.111) parts per unit time. Utilization of workstations at full rate of production can be 55.55 %, 88.88 %, 44.44 %, 100 %, 44.44 %, and 55.55 % respectively.

4.1 Flexibility of RAL

As RAL is equipped with the capacity and error recovery flexibilities both, its performance is evaluated under varying conditions for both of them. Flexibility is the ability of the system to respond effectively to change and these changes may include both internal and external changes.

(i) Capacity flexibility

As robot can be easily added or removed from the assembly line due to plug and play capability, simulation results for varying number of robots in terms of number of assembled parts (i.e. output) over a simulation time period of 1000 time units are plotted in Fig. 2. For the considered simulation period, theoretical output of the assembly line can be 111 products. It can be seen from the results that with an increase in the number of robots, system output also increases. As it can be observed that there is no significant difference in using 5 robots and 6 robots on its output. Therefore, system can run almost at its full capacity with less number of robots. The plot of simulation results follow a pattern similar to the product life cycle in the market place and thus the number of robots can be increased or decreased to match the demand of the product. Thus, the proposed RAL model has capacity flexibility. The spare robots of this assembly line during less demand period of the product may be used in other assembly lines in the organization. Robots can perform equally well in other assembly lines as they are multifunctional and programmable. However, to maintain the focus of the paper, utilization of the spare robots is not considered as the primary concern.

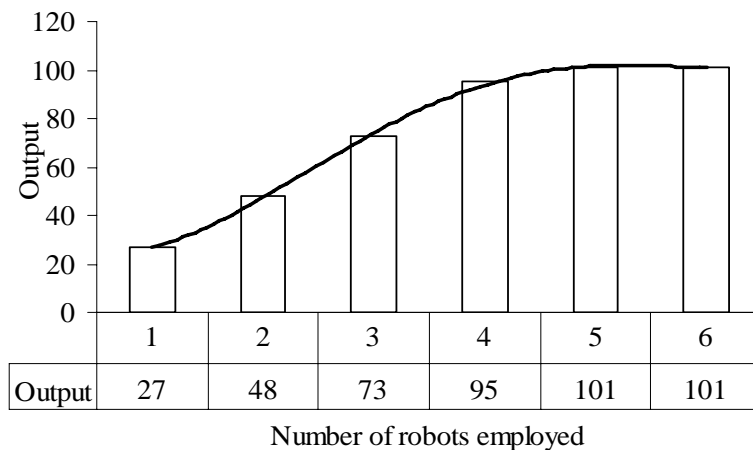


Figure 2: Outputs of six WS RAL employing different number of robots.

(ii) Error recovery flexibility

Error recovery flexibility is referred to as its ability to deal with internal disturbances, which occur during assembly, that endanger the operation of the whole system. The most important

feature of the proposed model is that it has protection against the shutting down of the whole assembly line in case of individual robot failures. For the system configuration shown in Fig. 1, robots accessibility constraints are given in Table I. With the failure of R_2 (say), it is pulled out of the line for repair and the remaining robots (R_1 , R_3 , and R_4) keep on working in the line with a decreased output. On removal of R_2 from the line, the accessibility constraints of the remaining robots are automatically changed by the controller as indicated in Table II. With three serving robots for the time being, each robot will have access to four workstations (i.e. $N-M-1$) instead of three, as was the case with four in-line robots. After the repair and reintroduction of R_2 , the controller again updates accessibility constraints as given in Table I.

Table II: Updated accessibility constraints.

$WS_x \backslash R_x$	WS_1	WS_2	WS_3	WS_4	WS_5	WS_6
R_1	1	1	1	1	0	0
R_2	F	F	F	F	F	F
R_3	0	1	1	1	1	0
R_4	0	0	1	1	1	1

F - failed

In case of failure of one or more robots, RAL works at a reduced capacity during repair of failed robot. When more robots are working in the system, difference in capacity change of the system due to failure of robots is not significant. In addition, generally the repair time of a robot is relatively less. Due to these facts, there will be no significant impact on the capacity of RAL even in case of robot failures. Thus, the proposed assembly line model is protected against the robot failures, as its output remains almost constant, by handling the internal disturbances in the form of robot failures intelligently. This flexibility also helps in proper maintenance of the serving robots. One or more robots can be pulled out of the line for regular maintenance work, without disrupting the production.

4.2 Resource utilization

On account of automated workstations, robots and other material handling devices, the initial investment of RAL is very high. For justification on economic grounds, it is thus necessary to estimate the number of robots to be included in the system for better utilization, before going to implement the proposed model. A six WSs system with varying number of robots is simulated for the study of resulting robot utilization (Table III). As the number of robots increases, utilization of the workstations approaches to their theoretical maximum values as shown in Fig 3. It can be seen that robot utilization decreases with the increase in the number of robots. Similarly, Fig. 4 shows the average utilization of robots and output in a six WS model while varying the number of robots. It can be seen that with the increase in the number of robots, system output also increases and thus the number of robots to be used is governed mainly by the product demand in the market. Therefore, when product is at its maturity stage, more number of robots are required, but during initial and declining stages of the product life cycle fewer number of robots can give the required output to satisfy the demand.

Table III: Utilizations of robots with six workstations.

	6 Robots	5 Robots	4 Robots	3 Robots	2 Robots	1 Robot
Robot 1	0.5444	0.5444	0.8774	0.9714	0.9404	0.9727
Robot 2	0.8524	0.8524	0.776	0.9694	0.7804	--
Robot 3	0.42	0.42	0.8694	0.6784	--	--
Robot 4	0.9224	0.9224	0.8694	--	--	--
Robot 5	0.408	0.9134	--	--	--	--
Robot 6	0.5054	--	--	--	--	--

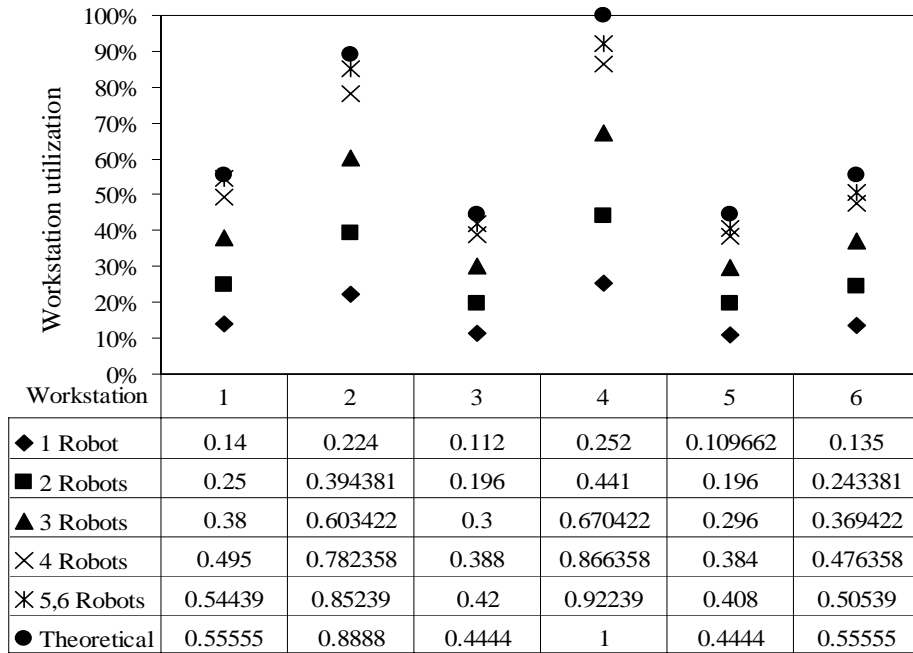


Figure 3: Workstation utilizations with different number of robots.

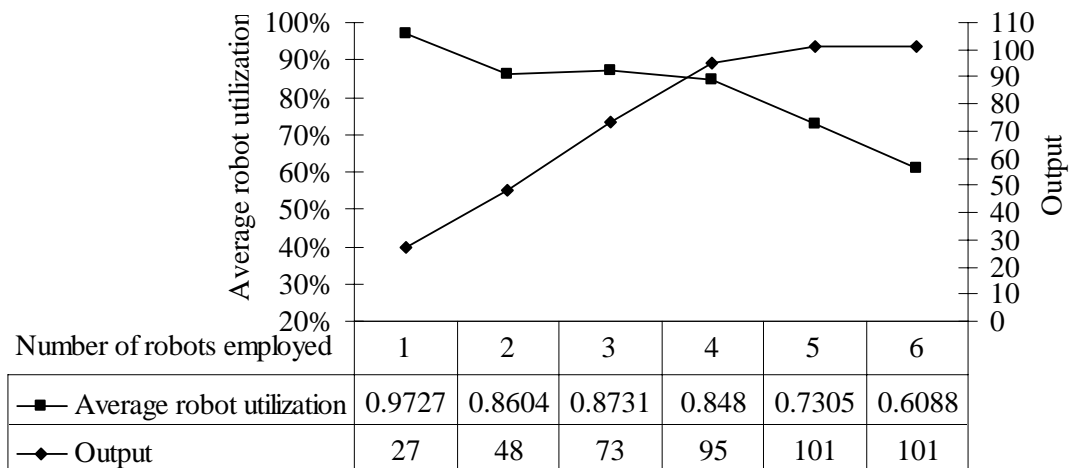


Figure 4: Average robot utilization and output of six WSs with different number of robots.

4.3 Effect of supervisory robot

Supervisory robot is one, which can serve all WSs and is placed on other side of the in-line robots. Fig. 5 depicts number of parts assembled for alternative configurations of RAL employing varying number of robots. It is clear from the figure that the use of supervisory robot increases output for any taken configuration except for 6+5 and 6+6. At these configurations, supervisory robot does not play substantial role as all in-line robots behave like dedicated robots. Moreover, the improvement in the output with the use of supervisory robot is diminishing in nature.

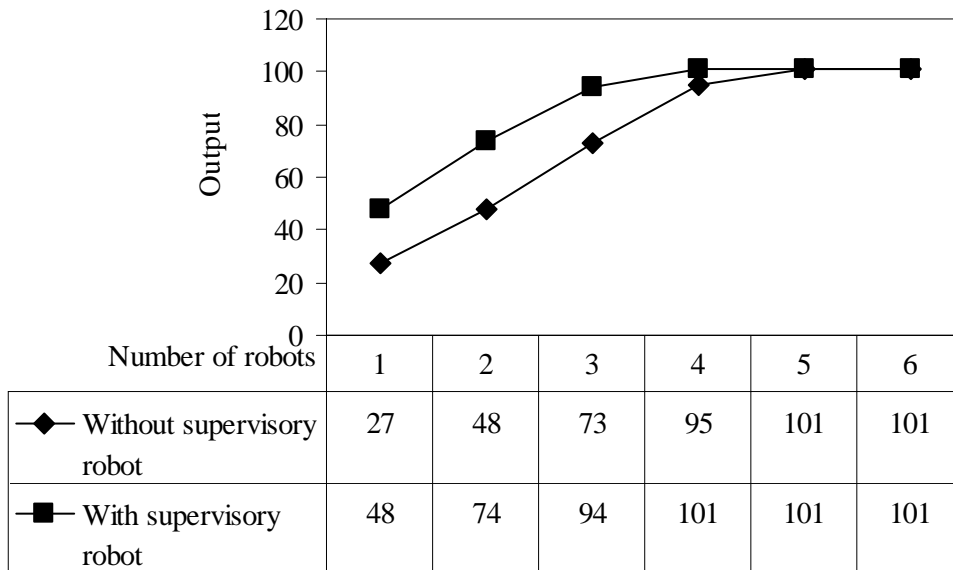


Figure 5: Effect of supervisory robot in different configurations.

4.4 Visualization of robots movement

A study is carried out to monitor the position of robots along guided path with respect to time. The position of robots at the start of simulation in a RAL of six workstations and three robots is similar to RAL shown in Fig. 1. As simulation clock advances, the movements of robots are recorded and graphs are drawn to visualize their movements as shown in Fig. 6. From this graph, locations of various robots can be visualized at any point of time. If the value of graph for a robot indicates a value k , then the robot is working at workstation k . If k is equal to '0' then the robot is idle and is at the same workstation where it was lastly working.

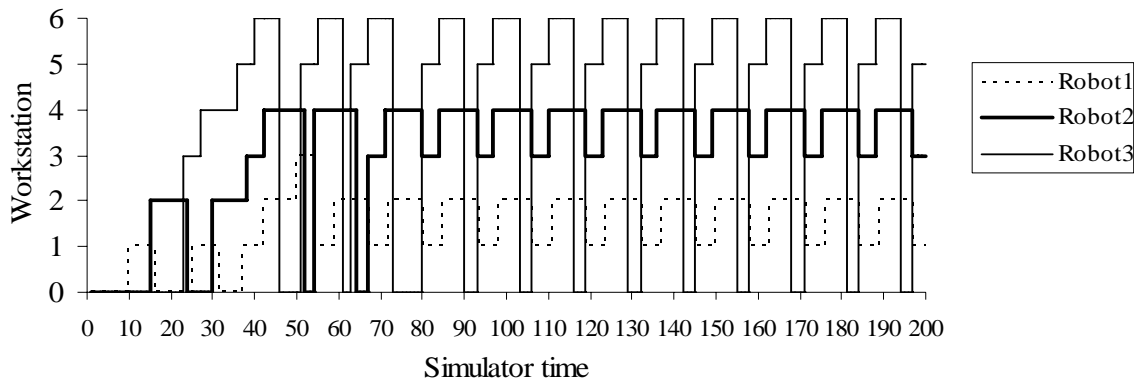


Figure 6: Visualization of robots movement.

5. CONCLUSION

The performance analysis of the considered model of RAL shows that it can be considered as a better alternative for assembly operations in modern day's production systems. Several performance measures have been evaluated (i.e. resource utilization, output, and flexibility) to prove the worth of the proposed approach. The following conclusions are drawn.

The proposed RAL model has both the capacity and error recovery flexibilities, which are much sought after features in assembly lines to offset the effects of demand fluctuation and malfunctioning of the system resources. Capacity flexibility can be imparted by varying the

number of in-line serving robots to match the desired demand pattern. It has also been shown that RAL keeps on working in the event of one or more robot failures with very less impact on output. Robot accessibility constraints table is updated dynamically by the system controller on the basis of the number of serving in-line robots at any point of time. It is important to note that these flexibilities are possible only when assembly line resources have plug and play capabilities.

Robots utilization can be improved by employing the right number of robots after conducting the simulation studies for the known demand. It may be noted that number of robots may be changed as and when there is a change in the demand of the product.

Simulation studies also establish the importance of supervisory robot in RAL. However, the improvement in output with supervisory robot is diminishing in nature, but it is quite substantial when fewer in-line robots are used.

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