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Simulating for 'resource optimization' in robot-assisted automatic assembly

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In most manufacturing systems emphasis is now given to resource flexibility in operation. The aim is to respond swiftly to changes in product mix and/or market demands.

Discrete event computer simulation is seen as a tool in defining a suitable system configuration at the preliminary design stage. Furthermore, simulation in dynamic form can represent the interactions between the system components and provide a detailed prediction of its performance.

Although many existing computer simulation packages have reached a good level of general purpose modelling, by and large they lack the required versatility to deal with some specific features of manufacturing systems. One such important area is the robot-assisted automatic assembly where minimization of non-productive activities in the product assembly cycle is of vital interest.

This paper introduces a flexible modelling technique which identifies the resource utilization and optimization levels during the individual processes of a product assembly cycle. Within the working constraints of an assembly system, an 'optimal' robot sequential cycle is obtained by implementing this modelling technique in GPSL (general purpose simulation language).

1 INTRODUCTION

The use of robots in assembly plants is almost entirely confined to repetitive tasks of relative simplicity. Many first generation robots with no sensory feedback are engaged in carrying out a sequence of operations such as picking up objects and placing or assembling them within accurate fixturing by mere dead reckoning (**1**). When complex parts feeding and orientation are required sensory feedback information is essential. Depending on the application the information monitoring system may include visual, tactile or proximity sensors (**2, 3**). The repeated positional accuracy of the robot is then enhanced considerably in some cases to ± 0.05 mm (**4**). Continuous improvement of these sensing devices aids positional control of the movements of robots and their capability for working in flexible environments.

However, primarily robots are applied to repetitive simple assembly tasks in order to replace human operators. Their use is intended to increase the overall utilization of equipment and materials through higher service dexterity. Their integration in fully automated workcentres is expected to introduce much desired flexibility in the batch assembly of products which could change in shape, size or quantity (**5**).

The proposed layout of the workplace and the degree of its service complexity determine the required robot versatility. The flexible working environment is expected to increase the utilization of the robot by reducing its idle time which is caused by the system bottlenecks, machine failures or late delivery of pallets. These considerations apply to the selection of robots to serve in an existing system or within a proposed layout. Therefore, if a limited sequence device or a first generation robot suffices, there is no need to introduce a more complicated second generation robot.

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Dynamic computer simulation of a workcentre and its intended operations provide valuable insight in the design stages of a flexible robot-managed automated cell.

2 SIMULATION TECHNIQUES

Heginbotham *et al.* (**6**) developed a discrete computer graphic simulation of a robot transferring objects from a moving belt. The robot was presented in a three-dimensional picture in a discrete number of positions, specifying the joint velocity and acceleration between each position. The robot was seen to carry out the required tasks. In this manner various possible robot working configurations were observed and the 'optimum' obtained. Using a similar simulation method Warnecke *et al.* (**7**) studied the feasibility of robot application to material handling in small to medium batch production systems. Using their two-dimensional layout planning model, they concluded that the 'optimum' robot working configurations correspond to radial workcentre layouts.

These types of computer simulation are regarded as micro-modelling techniques where the alternative robot movements and the corresponding joint velocities and accelerations are specified. Computer simulation may also be employed to investigate a macro-model of the robot/workcentre dynamic interaction (**8**). Here, one is not concerned with the specific movements of the robot arm but with the service routine of the robot and the operation sequence within the workcentre as a whole. The movements of the robot between the service stations and the duration of its activities there are represented by processing and travelling time arrays.

The simulation model measures the important performance parameters such as the utilizations of the robot and machines and the production/assembly rates for an existing layout. Significant workcell input governing parameters and conditions may include:

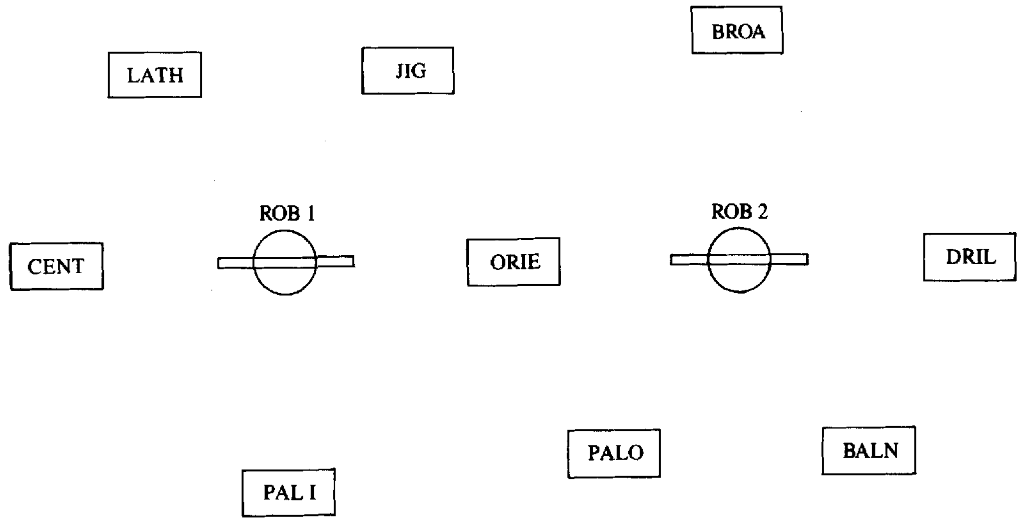

Fig. 1 Operation of a two-robot 'flexible cell'

(a) failure rates of machines and robot,
(b) inter-arrival distribution of pallets,
(c) provisions for inter-stage buffer stocks, and
(d) heuristically-based robot operational flexibility.

3 ROBOT UTILIZATION IN FLEXIBLE WORKING

The operation of a two-robot duplex 'flexible cell' is described in (**8**) (Fig. 1). Both cells have radial layouts, each served by its own dedicated robot, and each consists of a number of dissimilar workstations. No provision is made for inter-stage buffer stocks between the workstations.

The lack of alternative processing servers, coupled with zero buffer capacities, introduces severe inflexibility in the working routines of robots. Furthermore, long processing duration at a number of workheads form bottlenecks and cause under-utilization of robots and the preceding and following machines which remain idle (blocked or starved).

Utilizations of robots are increased, either by introducing buffer stores of adequate capacity at the bottleneck stations in order to increase the material flowrate preceding them, or by installing parallel servers at the bottlenecks to facilitate shorter throughput times. The choice between these alternatives lies in balancing the cost of excessive in-progress inventories against further investment in purchasing and installing the necessary capital equipment. Choosing the latter, reference (**8**) describes a general purpose simulation language (GPSL) model which determines the optimum resource level at each station (that is, the number of parallel servers), in order to increase the utilization of robots by an average of 75 per cent, and at the same time nearly double the production rate. However, the mean utilization of the workstations remains unchanged.

The discussions above show that while working flexibility leads to increased robot utilization and a higher production rate, the overall processing efficiency remains unaltered due to the problems of over-capacity and lack of optimization of the robots.

4 MODELLING FOR 'RESOURCE OPTIMIZATION'

Hitherto macro-level simulation has been used to determine system capacity, to balance production, to manage inventories, to relieve bottlenecks and to establish schedules (**9, 10, 11**). In all these applications the level of equipment utilization is an important performance measure, but little attention is given to the optimization level of the constituents of the system (such as robots or machines).

The difference between resource utilization and optimization is not always clearly defined. While the former represents the actual usage of the resource, the latter refers to its effectiveness in use. Traditionally, simulation has been viewed as a tool to obtain a 'near optimum' solution to a desired problem (both in configuration sizing or performance characteristics) by a long process of trial and error, with limited success in most cases (**12**).

Although for most heuristically-based problems, such as job shop scheduling, simulation techniques offer limited success, this is not true of many practical applications of a deterministic nature (**8**). The aim of this paper is to illustrate a method of simulation modelling for a robot/workcell constrained optimization using an appropriate industrial example and with the aid of GPSL.

General purpose simulation language is a discrete event, process interactive simulation language based on general purpose simulation system (GPSS) block formations (**13**) and is written in SIMULA (**14**). Details of some of the GPSS blocks and special feature GPSL blocks are provided in (**8**). Below, a newly formed 'machine/robot' block is discussed which allows the modelling of productive activities of machines and robots in operation.

Figure 2 shows this special form of the 'machine/robot' block. Each operation (that is job) cycle time t_i consists of two parts. One corresponds to the periods of resource activity and the other represents the idle times. In this way resource utilization is easily identified during each cycle time. Therefore, the machine/robot overall utilization is determined during a simulation run consisting of a number of operations. Furthermore, the active periods are subdivided into productive and non-productive durations, allowing evaluation of the resource optimization level.

Referring to Fig. 2, the ith cycle time is

$$t_i = (\mathrm{ap} + \mathrm{an} + \mathrm{p})_i = (\mathrm{Lp})_{i-1} - (\mathrm{Lp})_i \qquad (1)$$

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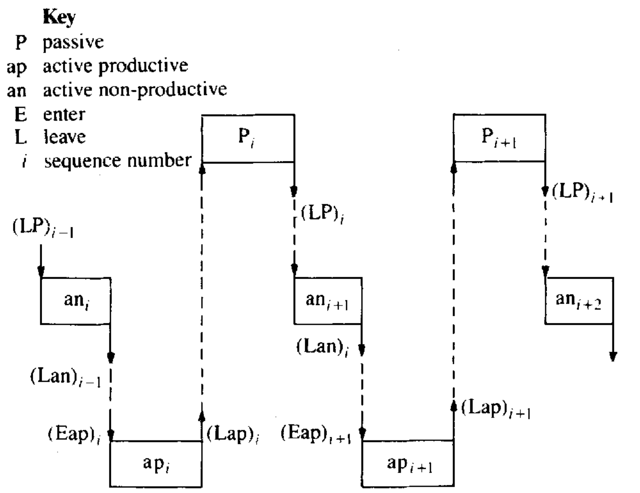

Fig. 2 Machine/robot block

Typically, the ith cycle can represent a partly robot-managed operation at an assembly station. The period $(an)_i$ represents the non-productive movements of the robot prior to the task engagement. These can take the following forms:

(a) movement of the robot arm with nothing in the gripper;
(b) the robot changing its gripper to perform the required task;
(c) the robot delivering parts to the assembly station.

The duration $(ap)_i$ corresponds to the actual engagement of the robot at the assembly head, and the passive interval is denoted by $(P)_i$. The boxes represent the modes of machine/robot operations during the sequential cycles i, $i + 1$, ... The arrows indicate the points of entry to and exit from each working mode ('enter' and 'leave' GPSS blocks).

5 AN INDUSTRIAL APPLICATION

Figure 3 shows a plan view of a proposed robot-assisted assembly cell. The cell layout is radial and consists of two assembly stations with an intermediate gripper storage bank. Station 1 consists of a pallet storage area and an assembly machine. Ejection and transferring the sub-assemblies from station 1 to station 2 is performed by a conveyor system. Station 2 has a buffer storage capacity of four pallets, and an assembly machine with two working heads using a common workplace area. Unloading of the finished assembly from this station is also effected via the same conveyor system. A first generation RRR-RR robot handles the part loading at both stations in addition to carrying out some part assembly operations there.

Figure 4 shows the product which is to be assembled. The pulley component is palletized and delivered to station 1 in the correct orientation for robot handling. The spacer and the bush are fed through and located by the assembly head at station 1. At station 2, the robot places the sub-assembly in the correct orientation within the fixtures. The first workhead inserts the pin. This is followed by the robot placing the washer. The turret is automatically indexed and the second workhead places and tightens the nut. A change of gripper is

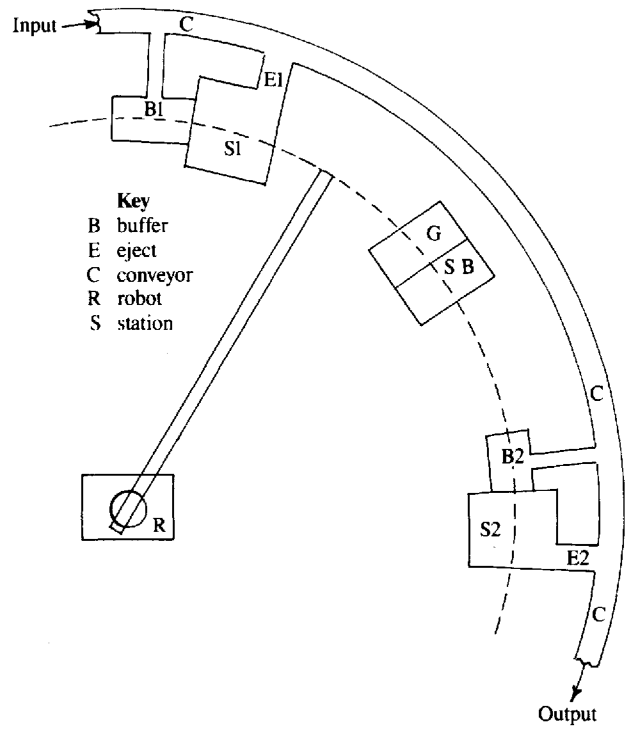

Fig. 3 Proposed robot-assisted assembly

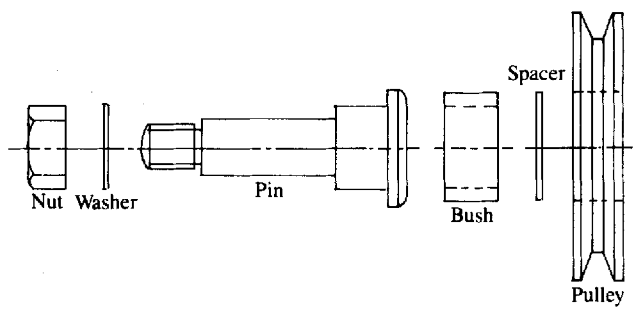

Fig. 4 Product to be assembled

required periodically as the robot works with either of the stations (Table 1). Table 2 provides the sequence of operations and their durations at each workstation.

There is an adequate supply of pallets to station 1 and of required components to all workheads in order to eliminate idle times there due to late delivery of parts. The conveyor speed can be adjusted to ensure that sub-assemblies arrive at the station 2 buffer store in time for robot loading and also to minimize congestion there.

Table 1 Sequence and duration of operations

Sequence	Operation	Duration s	Station	Gripper code
1	Depalletize pulley	35	S1	GRX11
2	Change gripper	50	GSB	—
3	Fetch sub-assembly	50	S2	GRX21
4	Load sub-assembly	45	S2	GRX21
5	Change gripper	50	GSB	—
6	Fetch and place washer	20	S2	GRX22

Notes
S_i station number
W_i workhead number
GSB Gripper storage bank
GR gripper
R robot

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Table 2 Sequence and duration of operations

Sequence	Operation	Duration s	Station/ robot	Gripper code (if robot)
1	Depalletize pulley	35	R	GRX11
2	Set up fixtures and inspect	120	S1	—
3	Position spacer and insert bush	50	S1/W1	—
4	Eject sub-assembly	10	C	—
5	Fetch sub-assembly	50	R	GRX21
6	Load sub-assembly	45	R	GRX21
7	Insert pin and rotate work	150	S2/W1	—
8	Fetch and place washer	20	R	GRX22
9	Index head and tighten nut	190	S2/W2	—
10	Eject assembly	10	C	—

Notes
S_j station number
W_i workhead number
GSB gripper storage bank
GR gripper
R robot

At the initial stage, the manufacturer's interest is in assessing the proposed cell layout and in particular in planning the operational sequence of the robot to obtain 100 per cent robot utilization. The important performance measures such as the mean utilization of workstations and the overall production rates are to be obtained and recommendations made to optimize further the system. To achieve an 'optimal' solution, the causes of transient behaviour such as failure of the machines, the robot and the conveyor system, as well as changes in assembly requirements, are to be ignored.

6 THE SIMULATION MODEL

A GPSL dynamic macro-model of the system is constructed on three distinct but interdependent levels:

(a) the dynamic overall system model (that is the proposed layout) with the modes of operation at both stations and the robot as outlined in Fig. 2;
(b) the parallel process models (Fig. 5);
(c) transactions (that is parts to be assembled) (**8**).

At any given time the system model contains a number of parallel process models (Fig. 5). A process model may be active or passive depending on the availability of the required resources. The components/subassemblies are modelled as transactions which move through the system model, progressing from one process model to the next until the completion of the assembly.

The passive process models collect information about queueing times of transactions. The active process models record the idle periods of machines and robot by registering the time elapsed between their respective passivation and activation times during a process. The system model updates these idle times by receiving the outputs from all the active process models and cross-referencing them for resource utilization. In the same manner, the system model determines the overall waiting time of jobs by collecting the outputs of the passive process models.

In GPSL modelling 'search' blocks are used to investigate whether an entity meets a specified condition (**8**).

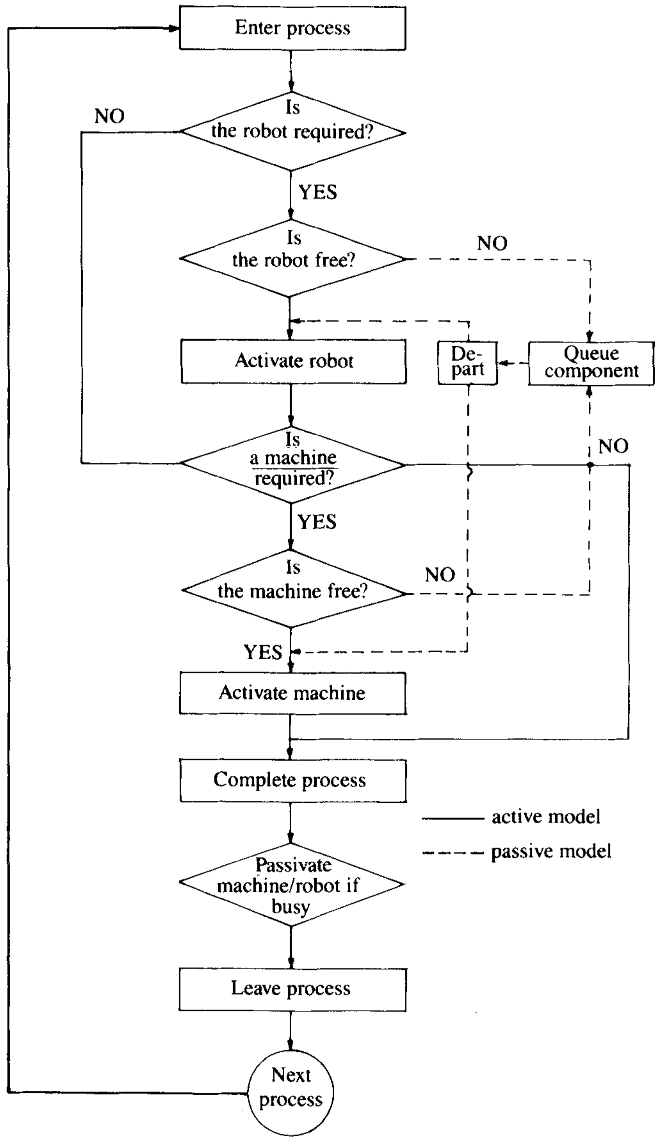

Fig. 5 A GPSL process model

In this application 100 per cent robot utilization is sought. Therefore, a 'search' block is employed to schedule the next operation of the robot at any given time during the simulation in order either to eliminate or to minimize its waiting times (that is the passive mode). The 'search' block continually compares the statistics received from all the process models which require robot assistance and determines the earliest available one for robot engagement. In this way a desired solution is achieved by a single run of the simulation model.

The robot sequential cycle alters during the initial parts of the simulation where work in progress builds up and a steady state condition emerges. A steady robot sequential cycle is then reached which corresponds to its highest attainable utilization.

7 RESULTS AND DISCUSSIONS

The initial conditions for this simulation envisage the availability of one pallet at station 1, an adequate supply of components at all workheads, and no subassemblies present at station 2.

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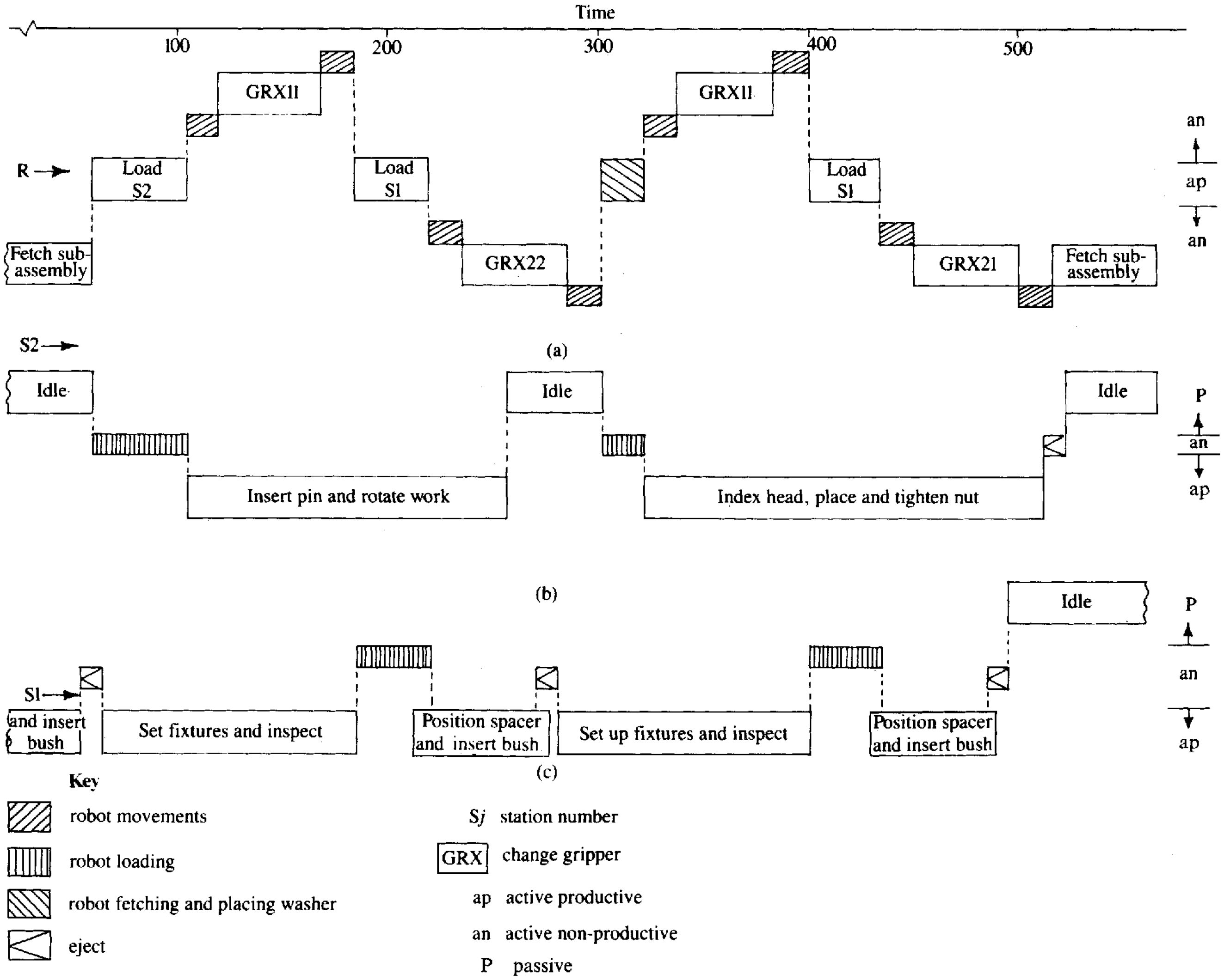

Fig. 6 Robot sequential cycles of operations

The steady state robot sequential cycle is shown in Fig. 6a. The corresponding activities at stations 1 and 2 are shown in Fig. 6b and c respectively. The passive, productive and non-productive modes of operation of both stations and the robot are indicated. There are in fact no idle times during the robot cycle (that is 100 per cent robot utilization). However, the low proportion of the robot's productive activities results in a much reduced optimization level of 26 per cent. The mean steady state utilization of the workstations is 88.5 per cent and the corresponding mean optimization level is 71.5 per cent.

The steady state condition is reached after 4500 s of simulation which involved 1.5 s (computer processing) of computation time on a CDC 855 mainframe machine.

The other important performance measures are:

(a) production rate = 14 products/h;
(b) average queue for robot = 4 processes;
(c) utilization of buffer at station 2 = 97 per cent;
(d) utilization of gripper bank = 39.5 per cent.

The robot sequential cycle in Fig. 6a provides the basis for some recommendations that can reduce its non-productive activities. In turn the increased robot optimization level would reduce its cycle time and enhance:

(a) the production rate;
(b) the mean utilization of workstations;
(c) the optimization of the system.

Recommendations can be made within the context of the system constraints which include the robot versatility and the assembly requirements for the product. It is decided that a multi-function gripper can be designed to handle the part loading at both the workstations (that is to replace GRX11 and GRX21). However, the multi-function gripper (that is GRY) would not be capable of the necessary fine positioning of the washer (effected by GRX22). The design and production of the gripper GRY would be cost effective if a significant change in production rate resulted (that is 2 or 3 products/h).

Therefore, a second simulation run is required. However, the modelling task is considerably reduced as the suitable robot sequential cycle has already been obtained by the previous simulation. There is no need to employ the 'search' block again. Instead, the robot working model (as in Fig. 2) is altered to include the sequence: load S2, load S1, fetch and place washer, load S1, and the gripper changeover time GRX11 $\rightleftharpoons$ GRX21 is set to zero.

The simulation results at the steady state condition are presented in Fig. 7a, b and c. The robot utilization remains at 100 per cent with its optimization level

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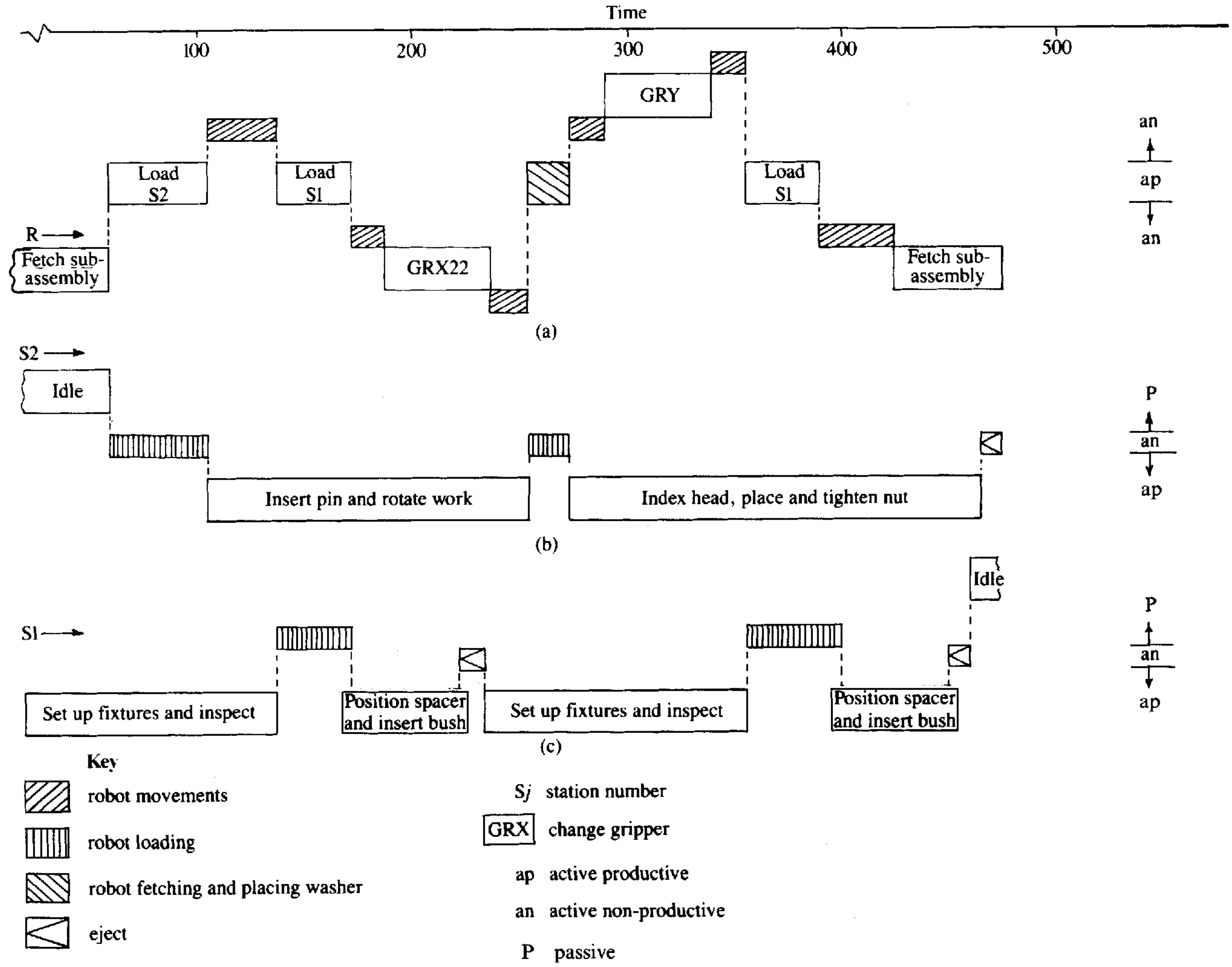

Fig. 7 Simulation results at the steady state condition

increased to 33 per cent. The mean utilization and optimization of the workstations are 96 and 82 per cent respectively. The other important performance measures are:

(a) production rate = 17 products/h;
(b) average queue for robot = 4 processes;
(c) utilization of buffer at station 2 = 95 per cent;
(d) utilization of gripper bank = 24.8 per cent.

8 CONCLUSIONS

A flexible modelling technique is outlined which identifies the resource utilization and optimization levels in the dynamic simulation of assembly systems. An 'optimal' resource sequential cycle is obtained using this modelling technique and constrained optimization of the system's proposed configuration.

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