Robot Time and Cost Management in the Application to Multiple Low-Volume Production Processes

Maria Caruana and Michael A. Saliba*

Department of Industrial and Manufacturing Engineering
University of Malta
Msida, Malta

Abstract

Typically, a manufacturing company will only consider the implementation of a robot to a production process if the annual product volume is high enough to ensure a high utilization of the robot and therefore an acceptable return on the investment. In particular, small and medium-sized enterprises (SMEs) often lack the production volumes, for each individual product or product family that they manufacture, that would justify the procurement of a robot using this traditional criterion. In this work we address the situation where a company, typically a SME, manufactures manually a number of substantially different products in batch and/or flow mode, where none of the individual annual volumes are high enough to justify the implementation of a dedicated robot to any part of the production, and we study the feasibility of employing a robot to several substantially different production processes within the company over a specified production period (e.g. one year). We show that this approach, through maximizing the exploitation of robot flexibility, can result in substantial cost savings by SMEs, while meeting production time targets and potentially improving product quality.

1. INTRODUCTION

Micro, small and medium-size enterprises can be considered as a major source of entrepreneurial skills, innovation and employment. It is in fact reported that in the 27 countries of the European Union, around 23 million SMEs provide around 75 million jobs – representing 99% of all enterprises. These figures stress the importance of these enterprises in the European economy [1]. Despite their importance, SMEs face great difficulties which are mainly due to lack of a research culture and limited in-house resources. European manufacturers are facing other big challenges aside from the financial crises including competition from developing economies, cost of materials, and competition from developed economies (non European Union) [2]. European SMEs need to invest in more R&D to provide more innovative, high-end products which would bring to light the difference between European manufacturers and Eastern ones [2]. This would mean that whilst the production of basic goods continues to shift eastwards, European companies would be at the forefront of innovative products and pioneering technologies.

A recent study on the Maltese manufacturing industry [3] shows that 40% of the companies surveyed adopt only fully manual manufacturing processes. The reason prevalently stated by the respondents is that the volumes involved are low and the variety is high. Other factors that hinder automating are the costs involved in such projects, lack of expertise and lack of time to investigate. The last three factors are highly common among the micro and small companies. Low volumes require more frequent changeovers, which is one of the main reasons for not automating. The unavailability of excellent changeover capability can lead to extensive production losses [4]. According to the study, robots and full automation are only used for high-volume production. Robots are currently only considered for production processes if the annual product volume is high enough to ensure a high utilization of the robot and therefore an acceptable return on the investment is guaranteed. This raises the question of whether the flexibility offered by robots is being truly exploited to the full. Companies totally exclude the possibility of using a robot in cases where there are a number of different products, where the volume of each product does not justify a robot for itself, but where however it could be feasible to share the robot between all the different products. The role of this project is to address this research gap by developing the right tool which can help companies test the feasibility of sharing a robot and show how the robot time and cost can be managed. It is pointed out that while the present paper focuses specifically on robot use, the general approach may also be applicable to other highly flexible or highly reconfigurable manufacturing systems.

* Corresponding author: Tel.: (++356) 2340-2924; E-mail: michael.saliba@um.edu.mt

2. THE CURRENT SCENARIO – THE USE OF ROBOTS TO HIGH-VOLUME PRODUCTION PROCESSES

Industrial robots are used to achieve two primary targets: a reduction in labour costs and an increase in productivity [5]. According to the 'Strategic Research Agenda for Robotics in Europe' [6], industrial robotics guarantees cost-effective production which Europe would lack due to relatively high labour costs. Apart from increasing productivity, industrial robots produce greater consistency and conformity with the customer requirements [6] [7] [8]. A significant advantage of investing in robotic automation is that it is reusable and reprogrammable should the product change [9].

It is inevitable that such a discussion on the implementation of robotics to substantially different production processes with low volumes will bring up concerns regarding changeover operations required. Figure 1, (adapted from [4]) shows generic behaviour of robot line output during changeover. The period from 'C' to 'X' is normally long (e.g. one or two years). The longer this period is, the less significant the changeover period will be. In fact, the frequency of changeovers will be smaller for large-volume orders.

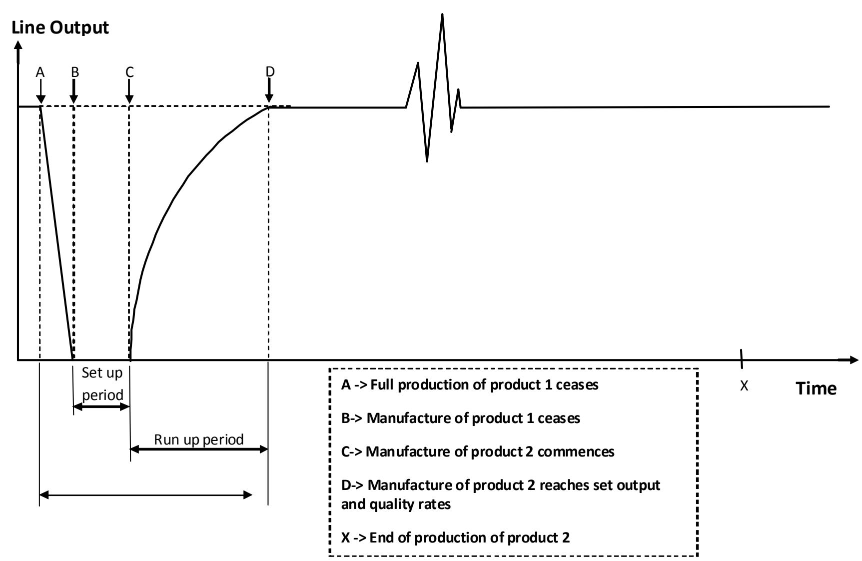

Figure 1 - Generic behaviour of line output during changeover (adapted from [4])

3. PROBLEM SCENARIO AND OBJECTIVES

If the output behaviour of Figure 1 were to be applied to low-volume production, then the period 'C' to 'X' would represent shorter periods (e.g. one month). Thus, projecting the same trend for a period of one year, there could be around twelve changeovers. At any time the robot could be 'busy', 'idle' or being 'set up'. In both the 'idle' and 'set up' modes, no value is being added to the product, however the 'set up' mode is necessary whereas the 'idle' mode may not be. The changeover period is not affected by the volume of the order. However, the frequency of changeover operations over a period of time changes according to the volumes to be produced.

Suppose a company has *'N'* orders, each of low to medium volume. Each different product requires a set of different tasks to be carried out. It is assumed that the products may be very dissimilar from each other. Currently, there would be '*N*' production lines. Each product has a task (or possibly more) that is currently being carried out manually, and these tasks are also different for each product. Since there is a small order for each product it is conventionally thought not to be feasible to invest in automation to carry out these tasks.

The role of this research is to test the feasibility of implementing a robot to replace the tasks being carried out manually in the above scenario. Owing to the low volumes involved, the robot has to be shared between all the different product types. The individual changeovers that will be incurred by resource sharing have a direct effect on overall completion time of the individual orders. The following objectives have been set:

- Develop algorithms that will search for the best way of using a robot over a number of production processes within the company portfolio over a specified period (e.g. one year);
- Develop a tool which uses the new algorithms to help companies in implementing the robotics solution.

This work is carried out in the context of a case study put forward by an industrial partner, and therefore the project also involves the following two industrial objectives:

- Carry out a factory-wide study to search for manual low volume processes that could technically be carried out by an industrial robot;
- Methodically find an optimal solution for robot implementation to these processes in the factory.

4. THEORY

4.1 TIME STUDY THEORY

We consider *N* different manufacturing systems that are producing the *N* products, with each system operating primarily in batch mode as shown in Figure 2. For every product *k*, we identify one station $s_{R_k k}$ that can benefit from conversion to robotic automation. Within this station (hereinafter referred to interchangeably as station SRKK) we make the general assumption that production is carried out in a flow line. One or more of the substations f_{ik} in the flow line are currently carried out manually and can potentially be replaced by a robot. Production of all batches starts simultaneously at time $t = 0$. It is noted that where a manufacturing system operates exclusively in flow mode, there is only one "batch" station (SRKK), whereas where a manufacturing system operates exclusively in batch mode, there is only one "flow" sub-station f_{1k}. Table 1 shows the notation that will be used throughout this section.

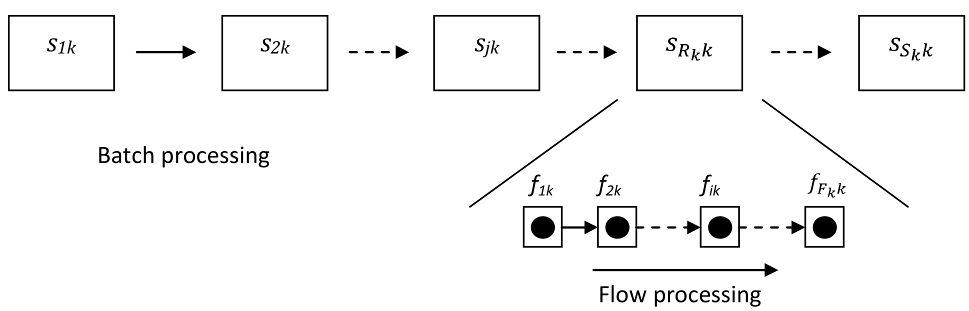

Figure 2 – Batch – flow combination

Table 1 - Notation

N	Number of different product batches
n_k	Number of parts in the batch of product *k*
S_k	Total number of batch processing stations for product *k*
s_{jk}	Batch station *j* of product *k*
R_k	Station number of the batch station where conversion from manual to robot use can occur
F_k	Total number of flow sub-stations in $s_{R_k k}$ in SRKK)
f_{ik}	Flow substation *i* of SRKK
t_{jk}	Task time at batch station *j* for product *k*
T_{Ak}	Total production time of batch *k* for all stations before SRKK
T_{Bk}	Total production time of batch *k* for all stations after SRKK
T_{Dk}	Delay time for batch *k* after it has arrived at SRKK, due to robot still working on another product
T_{Wk}	Waiting time for batch *k*, after it has arrived at SRKK, before production at SRKK can actually start
t_{ik}	Task time at flow substation *i* of SRKK
t_{Lk}	Longest substation task time in SRKK
TRA_k	Total time for the batch of product *k* to pass through station SRKK, in the fully manual system
TRB_k	Total time for the batch of product *k* to pass through station SRKK, in the system with the robot
$\tau_{m,n}$	Robot changeover time from product *m* to product *n*
T_k	Total time (from t=0) for product *k* to be completed
D_k	Due delivery time (from t=0) for the order of product batch *k*
B_k	Contingency buffer period between T_k and D_k, to be taken into account during scheduling

Although all the products may start being processed at their respective first stations s_{1k} at $t = 0$, the different products will arrive at their respective SRKK at different instances depending on the dynamics of the preceding stations. Before the incorporation of the robot, we have, for every product k:

$$T_{RA\,k} = \sum_{i=1}^{F_k} t_{ik} + (n_k - 1)t_{Lk} \tag{1}$$

$$T_{Ak} = n_k \sum_{j=1}^{R_k-1} t_{jk} \tag{2}$$

$$T_{Bk} = n_k \sum_{j=R_k+1}^{S_k} t_{jk} \tag{3}$$

Now, we consider the situation where one or more of the manual substations in SRKK, for every product k, have been replaced by a robot substation. Since there is only one robot, only one station SRKK can be operative at any time, and the problem becomes one of optimizing the scheduling of the robot among the products. If the robot is assigned to the products in the order of the numerical identifier k, i.e. first to the product assigned $k = 1$, then to the product assigned $k = 2$, and so on up to the product assigned $k = N$, we have:

$$T_{Wk} = \begin{cases} \tau_{(k-1),k} + T_{Dk} & if\ this\ expression > 0 \\ 0 & otherwise \end{cases} \tag{4}$$

where for $k = 1$, $\tau_{0,1}$ represents the set up time for a robot from non-use to production of product 1. Note that in cases when station $s_{R_{k-1}k-1}$ completes batch k–1 before batch k arrives, then $T_{Dk} < 0$.

Therefore,

$$T_k = T_{Ak} + T_{Wk} + T_{RB\,k} + T_{Bk} \tag{5}$$

where $T_{RB\,k}$ must be calculated in a manner similar to that given in Equation (1), following a technical study / design of the proposed new flow line that includes the robot. For product k to meet its due delivery date, we must have:

$$T_k \le D_k - B_k \tag{6}$$

4.2 COST-STUDY THEORY

In this study the relevant cost comparison is that related to stations SRKK, since the costs of the other stations remain unchanged after adoption of the robot. Table 2 shows the additional notation for the cost study.

Table 2 - Cost study notation

O_{Ak}	Number of operators in SRKK before incorporation of the robot, for product k
O_{Bk}	Number of operators in SRKK after incorporation of the robot, for product k
P_O	Salary/hour of operator at manual stations f_{ik}
P_T	Salary/hour of technician(s) that carry out the robot changeover tasks
C_M	Other miscellaneous additional costs due to robot (e.g. additional electricity and insurance costs)
C_{Ak}	Production cost for SRKK before incorporation of the robot, for product k
C_{Bk}	Production cost for SRKK after incorporation of the robot, for product k
T_C	Total time for all robot changeovers
C_A	Total production cost for stations SRKK before incorporation of the robot, for all products
C_B	Total production cost for stations SRKK after incorporation of the robot, for all products

Before incorporation of the robot, we have

$$C_{Ak} = O_{Ak} \times P_O \times T_{RA\,k} \tag{7}$$

$$C_A = \sum_{k=1}^{N} C_{Ak} \tag{8}$$

After incorporation of the robot, we have

$$T_C = \sum_{k=1}^{N} \tau_{(k-1),k} \tag{9}$$

$$C_{Bk} = O_{Bk} \times P_O \times T_{RB\,k} \tag{10}$$

$$C_B = \sum_{k=1}^{N} C_{Bk} + T_C P_T + C_M \tag{11}$$

Optimization of the robot scheduling involves the minimization of the cost difference ($C_B - C_A$).

5. METHODOLOGY OF THE SIMULATION TOOL

The methodology of the tool is shown in Figure 3. At the start, all of the data and the variables that do not depend on the robot schedule are entered by the user and/or are calculated by the program. For each product that exists, a corresponding file is created containing: due date, the batch size, the batch arrival time at the line (i.e. T_{Ak}), and information regarding each of the tasks in SRKK (including task number, robot flag indicating whether task requires a robot, and task time). Table 3 shows an example. Three other files are created containing a robot changeover time matrix, list of working shifts and maintenance periods respectively. The robot changeover time matrix contains information on the times associated with all the combinations of changeover between products.

Maintenance periods are scheduled beforehand and during such periods the robot is unavailable. Simulated production is brought to a halt and is continued thereafter. In the event of an unexpected occurrence during the *actual* production, the production manager would check how many items of each product have been processed and re-run the simulation with the new set of data, and a new plan is issued starting from the time of the occurrence.

The simulation program outputs the optimum robot schedule and the associated production cost saving $C_B - C_A$. The decision on whether to employ a robot for the given tasks is then taken by company management on the basis of various factors including return on capital investment for the automation, and comparison to other optimized non-robot automation and/or manual alternatives.

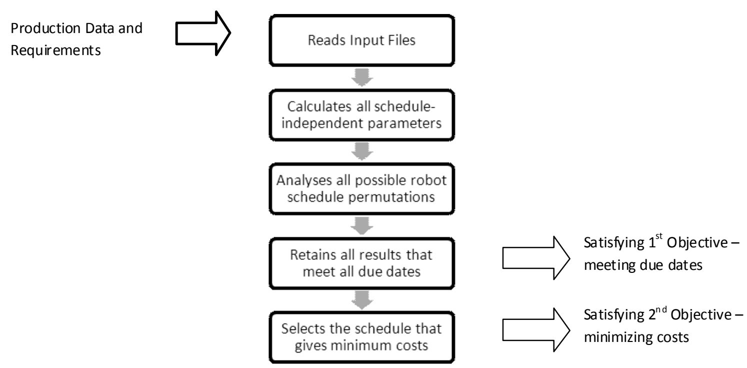

Figure 2 - Simulation Methodology

Table 3 – Product Information

Due date (min.)	180,000
Batch size	100,000
Batch Arrival Time(min.)	60,000
Task information: Task no., Robot Flag, Task time (min.)	T1 N 0.06
Task information: Task no., Robot Flag, Task time (min.)	T2 Y 0.05

6. ROBOT IMPLEMENTATION FOR VARIOUS LOW VOLUME PRODUCTS: A CASE STUDY

6.1 INTRODUCTION

The methodology and simulation were tested on a simple case study involving semi-automated production lines. The case study is based on data obtained from an industrial partner that produces small plastic toy-figurines. The case study involves three different products, herein referred to as Products A, B, and C. The three tasks necessary for each product are: injection moulding, printing, and packing, carried out in this order.

Before developing the solution, it was crucial to confirm and prioritize the objectives to be optimized. On consultations with the industrial partner, it was established that the first objective should be to meet due dates as initially set up by the customer in order to guarantee the company's goodwill. The second objective is to lower changeover costs. Human intervention is the major factor in a changeover, meaning that this activity entails a significant additional cost to the company. Consequently, minimization of changeover costs is often directly related to a minimization in changeover time.

6.2 DESCRIPTION OF THE CURRENT AND PROPOSED PACKING SYSTEM

The parts are first injected at the injection moulding department and are then passed to the printing department. Since these two tasks are carried out at two different departments, they are carried out in batch processing mode, with operators working three 8-hour shifts, 7 days a week. For the purpose of this case study we assume that all three products start production simultaneously at their respective Station 1 at time $t = 0$ (on Day 1). Each product will arrive at its respective packing line after all items of that product are ready from these two tasks.

The current task times are shown in Table 4. At Stations 3, although the respective parts corresponding to the different packing lines are completely different from one another, the products have similar task times and as a result the current systems are all balanced. The arrival time T_{Ak} for each batch k can be found using equation (2), the results of which are shown in Table 5. The total number of items n_k of each product is 400,000. At Stations 3, operators work one 8-hour shift per day, and currently the total completion time of each product is around 120 days.

Table 4- Current task times of all products

Station Number	Sub-station Number	Task	Product A Task time (min.)	Product B Task time (min.)	Product C Task Time (min.)
1		Injection Moulding	0.1	0.09	0.1
2		Printing	0.09	0.026	0.05
3	3.1	Operator (packing)	0.045	0.045	0.045
	3.2	Packing Machine (A4)	0.045	0.045	0.045

Table 5 - Arrival times and due dates

Product	Total time for tasks preceding SRKK (days)	Product Due Date (days)
A	53	120
B	32	365
C	42	170

Each product has a corresponding packing line having similar setups. In each case three packing operators sit along the packing line, and a packing machine 'A4' is located at the end of the line as shown in Figure 4. The conveyor is sectioned into small compartments. Each operator located along the conveyor puts one small part in each bin, meaning that finally there will be three parts in each bin. As already explained the aim is to test the economic feasibility of replacing one (or more) operators with a robot system for these particular products which have been identified by the company as possible robot projects.

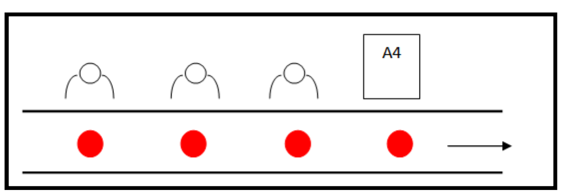

Figure 4 - Current Packing Line Layout for a product

An analysis of the implementation of a 4-axis SCARA robot would be appropriate for our case-study. When it comes to estimating the time taken for the robot to carry out the currently manual tasks, care has to be taken to minimize any machine wait time since this would reduce the efficiency of the production line. The task time for the robot can be estimated by adapting the work in [11] on robot time and motion. The distance that has to be covered by the robot is approximately 90 cm. A distance of 100cm at a peak velocity of 100cm/s is estimated to take around 1.4 seconds. With these approximations the case study will be as follows. The robot can replace two operators and place two parts in the bin in succession. The remaining operator can place one part in the bin. Consequently, the distance traversed by the robot will be doubled. The task time for the operators will remain 0.045 min (same as the packing machine at the end-of-line), whereas the robot will take around 2.7 seconds equivalent to 0.045 min. Thus the packing line will be balanced. The operators will work an eight-hour shift seven days a week. The robot changeover time matrix is shown in Table 6. The technicians that carry out the changeovers work one eight-hour shift per day. For this case study we assume that there are no maintenance interruptions, and also that $C_M = 0$.

Table 6 - Robot Changeover Time Matrix (minutes)

To \ From	A	B	C
A	0	2880	5760
B	2000	0	3000
C	5000	2850	0

6.3 COSTS FOR THE MANUAL SYSTEM

Product A currently has 3 operators in SRKK, each carrying out a different task. In our case, the task time for each product of batch k in SRKK is 0.045 min. Therefore, to finish the whole batch k, each worker works for 18,000 minutes (300 hours). The total operator working time for the current packing system are shown in Table 7.

Table 7 - Total operator working time for the current packing system

Working time (mins.) required for each task			
	Product A	**Product B**	**Product C**
Operator 1	0.045 min x 400,000 = 18,000	0.045 min x 400,000 = 18,000	0.045 min x 400,000 = 18,000
Operator 2	0.045 min x 400,000 = 18,000	0.045 min x 400,000 = 18,000	0.045 min x 400,000 = 18,000
Operator 3	0.045 min x 400,000 = 18,000	0.045 min x 400,000 = 18,000	0.045 min x 400,000 = 18,000

We assume that an operator is paid at €6.00 per hour; and that each operator incurs extra costs for the company which brings the total amount to €8.00 per hour. Therefore, the total operator costs for one product type amount to €7,200. Since these particular products have the same task times then the total operator costs for each product in this case study will be equal. As a result the company has an overall labour cost of **€21,600** for Stations 3 of the production of 400,000 items of the three products.

6.4 PROPOSED SYSTEM COSTS

The proposed new system requires one operator per packing line, a robot which will be shared amongst all packing lines, and a technician for the changeover operations. Knowing O_{Bk} and P_O and T_{RBk}, equation (10) can be used to find the operator cost for each SRKK with the new system. The total operator costs for one product amount to €2,400. Assuming that the robot changeover technician costs the company €15.00 an hour, we can estimate the total changeover costs, and consequently the total labour costs, associated with each schedule permutation.

6.5 RESULTS AND DISCUSSION

The simulation program was used to analyse the above scenario. The results show that if the robot is applied to the production of the products in either of the orders B-C-A, C-A-B, or C-B-A, then Product A will not meet the due date. For the permutation A-B-C, Product C will not meet the due date. Thus the only schedule permutations that pass the first acceptance condition of the simulation are sequences A-C-B and B-A-C. The cost analysis of these two alternatives shows that sequence B-A-C will result, marginally, in the lower total labour costs for the robot-assisted production of 400,000 items of the three products in Stations 3, amounting to **€9,170**. The corresponding labour costs for sequence A-C-B are **€9,200**.

The closeness of the cost results warrants further consideration of the product completion times under the two sequences, in relation to the due delivery dates. These data are shown in Table 8. The results show that although the labour costs for sequence B-A-C will be marginally lower than those for A-C-B, the former sequence will result in Products A and C being completed considerably close to their due dates, whereas in the latter sequence all three products will be completed a considerable time before their respective due dates. Indeed if the contingency buffer period B_k is set to 10 days for each of the three products, sequence B-A-C will fail on account of both products A and C. Thus, taking the completion dates as well as the production costs into consideration, it is concluded that sequence A-C-B would be the preferred option.

Table 8 – Product completion dates

Product	Due date (days)	Completion date (days)	
		Sequence A-C-B	Sequence B-A-C
A	120	91	113
B	365	183	70
C	170	139	161

An analysis of the costs shows a saving of **€11,200** in total labour costs, for a robot utilization of 140 days (including both set-up and production times, and assuming a set up time of 10 days for the production of Product A). If further medium-volume products can be included into the scheme to double the robot utilization to 280 days per year, leaving 85 days of robot availability for maintenance, training, shutdowns, and other contingencies, then the application of the robot can result in an annual labour cost saving of over **€22,000** per year for this company. Taking into account the current market prices of industrial robots, and including also ancillary expenses related to the robot, these results indicate that the return on investment for the incorporation of a robot in this scenario may be achievable in less than two years.

7. CONCLUSION

In this work we have proposed and analysed a scenario where the non-conventional application of an industrial robot to the manufacture of various low to medium volume products can result in substantial production cost savings for a manufacturing company. The study addresses a widespread misconception in the manufacturing community, that when the production volume of a product is “too low”, the use of robots is not economically feasible. Our results indicate that where a sufficient number of low or medium volume production processes, even if these are very different from each other, can be brought to share a single or limited robot resource, the potential economic returns can be substantial. In this approach the flexibility of industrial robots is truly exploited. The challenge, addressed in this work, lies in optimizing the scheduling of the robot resource between the products, in ensuring that all products meet their delivery dates, and in maximizing the utilization of the robot resource.

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