Looking for Optimum Feeding Sequences in a Manufacturing Cell with Four Parallel Machines *

Raúl Suárez Jan Rosell
Institut d'Organització i Control de Sistemes Industrials (IOC-UPC)
Diagonal 647, 08028 Barcelona, SPAIN – e-mails:{suarez,rosell}@ioc.upc.es

Abstract

The paper deals with the problem of optimum feeding sequences in manufacturing cells with machines fed by robots. In particular a real complete problem with four machines working on two pallets each one, fed by one robot and with random assistance requirements, is introduced and analyzed. The cell has been modeled and simulation results for different feeding sequences are presented as well as a discussion about the criteria for an optimum sequence search.

1 Introduction

The problem that originates this work was stated by a car-part manufacturing company that has a manufacturing cell with four parallel machines fed by a robot (the cell is described in detail in Section 2) and wants to optimize its productivity considering that the machines need some assistance from a human operator after a period of operating time. The parameter to be optimized is the waste time that the machines spend without working while they are waiting for the robot to feed them. The questions were: Which is the best sequence to feed the machines? Should the robot feed the machines in a fixed sequence or with some variable sequence like, for instance, using a FIFO queue (Fist In First Out)? In case of a fixed sequence, which one is the best?

The type of problem is not equivalent to any "standard" one described in the related literature (typically, robotized manufacturing cells are considered as the problem of feeding two or three machines with parts that have to pass through all of them, see for instance [1] [2] [5]), so no theoretical approach is available. Nevertheless, discrete-event simulation provides with the methodology to analyze and compare the system performance with different feeding sequences (see for instance [3]). Petri Nets were also used for the simulation and analysis of manufacturing cells of similar type (see for instance [4]). For the company particular case, we started with a simulation of the cell, trying to find out some useful conclusions and to open the problem in order to look for general solutions in future works. In this line, the paper presents some simulation results of the cell that lead to some particular conclusions and also some reasoning about how to model the problem in order to look for an optimum solution.

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2 Description of the Cell

Figure 1 shows a layout of the manufacturing cell. The cell is composed of four machines (m_i, with $i = 1, ..., 4$), all of them of the same type. Each machine operates alternatively over two pallets, A and B. The robot loads the parts into one pallet while the machine is working on the other pallet.

Each part to be manufactured must be first loaded into pallet A of any machine, where a set of operations leave it in a medium-processed state. Then, the part must be removed from that pallet and loaded into pallet B of any machine (it can be the same machine), where another set of operations leave it in the final state (unprocessed and medium-processed parts will be called type A and type B parts respectively).

The parts are loaded into the pallets and unloaded from them by a 6-dof robot that uses a rail to move from one machine to another. Once a part has been loaded in a pallet, a set of bridles must be closed to fix the part before the pallets turn to put the loaded pallet in the working side of the machine. On the other hand, after the turn of the pallets, the robot cannot recover the part in the pallet that leaves the working side until the bridles are opened. During regular activity, any load operation implies a previous unload operation of the pallet, therefore the time considered for loading a machine includes the corresponding unload action.

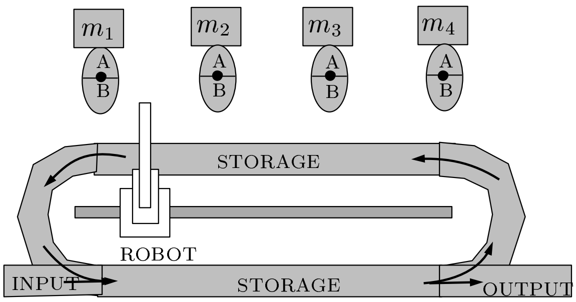


Figure 1: *Layout of the manufacturing cell.*

There is an auxiliary storage line where the robot can put the parts unloaded from the machines and recover them when necessary. Completely unprocessed parts are automatically supplied to this storage line, and therefore the robot always has direct access to either unprocessed parts as well as to medium-processed parts.

Each machine uses about 25 different tools for the operations on both pallet A and pallet B, and these tools have to be replaced after a number of operations. Since the life of each tool is different, the result is that the machine needs assistance from a human operator after a period of time that randomly varies within a given range. In this situation the machine stops working until a human operator replaces the corresponding tools and put it on-line again. During the first cycle after the assistance for tool replacement, the operator has to check the machine performance with the new tools, and this produces a checking cycle that lasts more than the regular one.

Nomenclature:

t_{wa}, t_{wb}: machine working time on pallets A and B.

t_{r1}, t_{r2}, t_{r3}: time for the displacements of the robot to a next, second and third machine, respectively, from the current one.

t_{la}, t_{lb}: loading time for pallets A and B (include unloading the parts already processed in the pallet).

t_{ca}, t_{cb}: time for closing the bridles in pallets A and B.

t_{oa}, t_{ob}: time for opening the bridles in pallets A and B.

t_t: pallet turning time (changing positions between pallets A and B).

t_s: machine working time before assistance request.

t_{a1}: assistance time by the operator.

t_{a2}: checking time by the operator in the machine cycle after the assistance.

The nominal times provided by the company for a given part were: t_{wa}= 4'11", t_{wb}= 3'24", t_{r1}= 6.5", t_{r2}= 10,25", t_{r3}=14" t_{la}= 47", t_{lb}= 55", t_{ca}= 28", t_{cb}= 30", t_{oa}=12", t_{ob}=12", t_t=14", 30'$\leq t_s \leq$ 150', t_{a1}= 2', and t_{a2}= 1'.

3 Feeding Strategies

The following strategies were initially considered for simulation:

Fixed sequences

Fixed machine and fixed pallet (FMFP). The machine sequence is $m_1 - m_2 - m_3 - m_4$, and the robot feeds first the pallets A of all the machines and then, in the next passing, all the pallets B. A machine is skipped if it is being assisted by the operator.

Fixed machine and free pallet (FM-I). The machine sequence is $m_1 - m_2 - m_3 - m_4$ feeding the pallet, either A or B, that the machine needs at the loading time. A machine is skipped if it is being assisted by the operator.

Fixed machine and free pallet (FM-II). The machine sequence is $m_1 - m_2 - m_3 - m_4$ feeding the pallet, either A or B, that the machine needs at the loading time. A machine is skipped if it is not ready at the time of its turn in the sequence, either due to the operator assistance or just because it is still working on another part.

Only fixed sequences that include all the machines before repeating any of them were considered. In some particular cases there may be better solutions if this condition is relaxed, but that would mean that there are machines that in nominal conditions double the production of some others, which produces undesired effects like, for instance, different maintenance routines.

Variable sequences

First In First Out (FIFO). Each time a machine has finished the work on a part, the pallet has turned, and the bridles have been opened, the machine is added to a queue. The robot feeds always the first machine in that queue. A variation of this strategy is the inclusion of a machine in the queue as soon as its pallets turn, before waiting for the bridles opening.

Optimization of a cost function (CFO). Once the robot has loaded a machine and have to choose the next one, the following cost function is computed for each machine: the time that the robot needs to arrive to the machine plus the time that the machine needs to be ready for a new load. The machine with the minimum cost is selected. The finish-time for each machine is obtained as the sum of the present time at the end of the loading operation plus the time for closing the bridles, turn the pallets, process the part, turn the pallets again and open the bridles. With this strategy, if two machines need the robot serving at the same time the robot will go to the closest one, and between two machines at the same distance the robot will go to the one that first needs to be loaded. Although very good results were obtained in simulations with this strategy, it was not considered for application in the real cell because the computation of the cost function requires a clock and numerical operations (note that the other strategies require only binary causal signals, i.e. the strategies work considering only binary signals available at the moment of the decision).

4 Simulations

Two simulators of the cell were implemented, one using Arena 3.51 (Systems Modeling Corporation) and another using Maple V release 5 (Waterloo Maple Inc.). The machine unproductive times (due to the waiting time for the robot, the waiting time for the operator and the operator assistance time) for each strategy have been computed. The simulations were done considering the cell working full day during a month. The number of experiments per case ensures a 95% confidence interval for the given least significant digit of each mean value (shown in percentage). Considering the initial nominal times (listed in Section 2) the results for each strategy were:

Strategy	Waiting for robot	Waiting for operator	Operator assistance
FMFP	5.72%	0.57%	5.53%
FM-I	0.91%	0.60%	5.64%
FM-II	0.17%	0.55%	5.66%
FIFO	0.045%	0.56%	5.66%

It is clear from these results that the time the machines wait for the robot is highly dependent on the feeding strategy, being the FIFO strategy up to two orders of magnitude better than the FMFP. This is quite relevant in terms of optimizing the production of the cell. The time that the machines wait for the operator and the time of the operator assistance are independent of the feeding strategy (nevertheless, there is a small correlation because if a strategy makes the machines to wait a lot for the robot the machine tools last for more time and the average of assistance by the operator is slightly smaller).

Running the same simulations for different machine working times on pallets A and B the following results were obtained.

Strategy	t_{wa}=251 t_{wb}=204	t_{wa}=239 t_{wb}=207	t_{wa}=240 t_{wb}=180	t_{wa}=210 t_{wb}=150
FMFP	5.72%	5.72%	5.98%	6.43%
FM-I	0.91%	0.86%	0.91%	2.11%
FM-II	0.17%	0.20%	1.45%	12.16%
FIFO	0.045%	0.067%	1.93%	13.37%

These results show that the best strategy varies with the machine working time. The lesser flexible the strategy the smaller are the influence of the machine working time in the machine waste time while waiting for the robot. A clear example are the figures obtained for the FMFP strategy. On the other extreme, the most flexible strategy (FIFO) varies a lot for different machine working times, going from two orders of magnitud better than FMFP to a worst performance. When the machines are fast enough compared with the robot movements, the FIFO strategy makes the robot to spend a lot of time traveling from one machine to another, with the possibility of passing in front of a machine ready to be loaded without loading it. Thus, the selection of the best strategy is not evident. The determination of the exact function that indicates the optimum sequence considering all the variables is a hard work. Nevertheless, some guidelines can be obtained from a first analysis of this particular problem.

5 Problem Modeling/Analysis

Let us define:

Machine Activity (MA): the time that one machine needs after being fed by the robot to be ready for a new load.

Robot Activity (RA): the time that the robot needs, after feeding one machine m_i, to feed all the others available machines (i.e. those that are not under assistance) and be ready to feed again the machine m_i. The robot activity can be divided into two subactivities:

Robot Moves (RM): the time due to the robot moves from one machine to another during RA.

Robot loads (RL): the time dedicated to load the machines during RA.

If the goal is to avoid waste time of the machines during production, then the following inequality must be satisfied,

$$MA \geq RA = RM + RL \tag{1}$$

i.e. after feeding a machine m_i the robot must be able to visit all the other machines, feed them and return to m_i before m_i is ready for a new load. In absence of perturbations, as long as inequality (1) is satisfied it makes non-sense to reduce the loading time (reduce RL) or to increase the velocity of the robot when it moves from one machine to another (reduce RM). On the other hand, in order to optimize productivity, the left member of inequality (1) should be minimized (reduce MA) up to the limit imposed by RA. If $MA > RA$ then the robot has to wait in front of a machine until it finishes the work and become ready to be fed.

The terms of inequality (1) are analyzed in the following subsections for the particular problem we are considering. First, for the fixed sequences, the machine sequences and the pallet sequences are analyzed. Then, the effects of variable sequences and machine assistance are outlined.

5.1 Machine Activity (MA)

After being served by the robot, the machine requieres some time to be ready for a new load due to the processes of closing bridles on the incoming part, turning the pallets, and opening the bridles of the processed part, so the machine cannot be reloaded before a time $t_{ca} + t_t + t_{ob}$ or $t_{cb} + t_t + t_{oa}$ if the loaded part was type A or B respectively. This is a lower bound for MA.

On the other hand, the maximum value of MA that ensures that the machine will not wait for the robot (i.e. no introduction of waste time) and therefore to be considered as a constraint in inequality (1) is, after loading a type A part,

$$MA = MA_a = t_{ca} + t_t + t_{wa} - t_{cb} - t_{lb} \tag{2}$$

and after loading a type B part,

$$MA = MA_b = t_{cb} + t_t + t_{wb} - t_{ca} - t_{la} \tag{3}$$

Figure 2 shows a machine cycle with the maximum MA that ensures no waste time.

5.2 Robot Activity (RA)

5.2.1 Robot Moves (RM)

RM depends on the sequence the robot follows to feed the machines. Since the robot must feed all the ma-

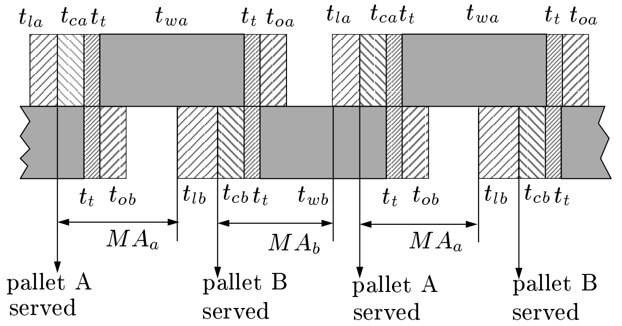


Figure 2: *Machine cycle showing the maximum MA.*

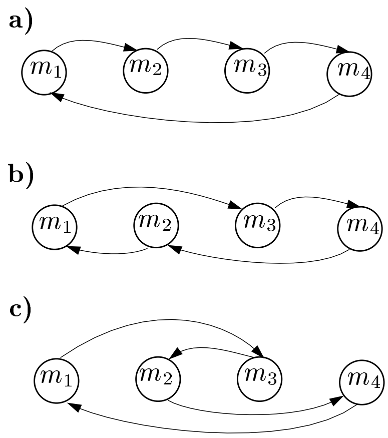


Figure 3: *Possible types of machine feeding sequences.*

chines before feeding twice one of them, there are only three different possible types of sequences (since all the machines are equal any other sequence can be reduce to one of these three types)(Figure 3):

a) Sequence: $m_1 - m_2 - m_3 - m_4$. This sequence implies three moves with duration t_{r1} and one with duration t_{r3} (the return from m_4 to m_1). Then,

$$RM = RM_1 = 3t_{r1} + t_{r3} \tag{4}$$

b) Sequence: $m_1 - m_3 - m_4 - m_2$. This sequence implies two moves with duration t_{r1} and two with duration t_{r2}. Then,

$$RM = RM_2 = 2t_{r1} + 2t_{r2} \tag{5}$$

c) Sequence: $m_1 - m_3 - m_2 - m_4$. This sequence implies one move with duration t_{r1}, two with duration t_{r2}, and one with duration t_{r3}. Then,

$$RM = RM_3 = t_{r1} + 2t_{r2} + t_{r3} \tag{6}$$

Since $t_{r3} \geq t_{r2} \geq t_{r1}$ it is evident that RM_3 is always worse than RM_1 and RM_2 so sequence (c) produces the worst RM. On the other hand, the convenience of RM_1 or RM_2 depends on the ratios between t_{r1}, t_{r2} and t_{r3}. For the typical trapezoidal velocity profile of a robot move (constant acceleration period, maximum velocity period, and constant deceleration period) $t_{r1} + t_{r3} \leq 2t_{r2}$ then $RM_1 \leq RM_2$, and therefore sequence (a) is preferred to sequence (b). Obviously, if a machine is being assisted, and therefore it is skipped by the robot, RM is smaller than in a regular situation. As a conclusion, sequence (a) produces the shortest RM.

5.2.2 Robot Loads (RL)

RL depends on the sequence of types of parts (i.e. type of pallet) that the robot loads into each machine (with independence of the position of the machine). Since there are two types of parts (A and B) and four machines, there are, initially, sixteen different combinations; nevertheless, since each machine has to process different type of parts in two consecutive cycles, the possible different sequences are reduced to eight, namely (subindices p, q, r and s take values from 1 to 4 with $p \neq q \neq r \neq s$):

	pallets of machine				pallets of machine			
	m_p	m_q	m_r	m_s	m_p	m_q	m_r	m_s
a)	A	A	A	A	B	B	B	B
b)	A	A	A	B	B	B	B	A
c)	A	A	B	A	B	B	A	B
d)	A	A	B	B	B	B	A	A
e)	A	B	A	A	B	A	B	B
f)	A	B	A	B	B	A	B	A
g)	A	B	B	A	B	A	A	B
h)	A	B	B	B	B	A	A	A

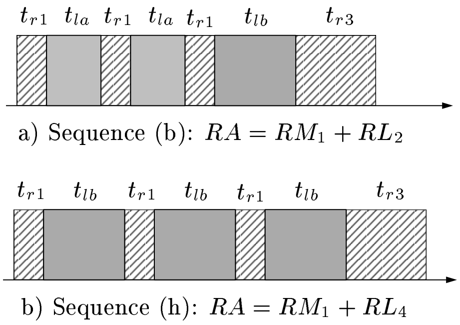
Thus, when all the machines are not under assistance, the robot has to feed three machines before repeating one of them. In this case, the following situations are possible:

- In all sequences (a) to (h), at some point the robot has to feed consecutively: one part A and two parts B or two parts A and one part B. In these cases, RL is determined by one of the following expressions,

$$RL = RL_1 = t_{la} + 2t_{lb} \tag{7}$$
$$RL = RL_2 = 2t_{la} + t_{lb} \tag{8}$$

- In the sequences (a),(b),(d) and (h), at some point the robot also has to feed consecutively: three parts A and three parts B. In these cases, RL is determined by one of the following expressions,

$$RL = RL_3 = 3t_{la} \tag{9}$$
$$RL = RL_4 = 3t_{lb} \tag{10}$$



a) Sequence (b): $RA = RM_1 + RL_2$

b) Sequence (h): $RA = RM_1 + RL_4$

Figure 4: *Two examples of robot activity RA.*

Thus, if $t_{la} = t_{lb}$ any sequence from (a) to (h) implies the same RL, but if $t_{la} \neq t_{lb}$ then sequences (a),(b),(d) and (h) impose two additional constraints, being one of them the worst case constraint (i.e. highest value of RL), RL_3 if $t_{la} > t_{lb}$ and RL_4 otherwise. As a conclusion, any of the sequence (c),(e),(f) or (g) is preferred.

Figure 4 shows two examples of RA, considering $t_{la} < t_{lb}$. In both cases the robot has just loaded m_1 and then follows the sequence $m_2 - m_3 - m_4$ (then $RM = RM_1$), but in the first case loading pallets A, A and B, respectively, i.e. pallet sequence (b) (considering $[p, q, r, s] = [1, 2, 3, 4]$), and in the second example loading three pallets B, i.e. pallet sequence (h).

5.3 Effect of Variable Sequences

Variable sequences are determined by a heuristic that, based on the available information at the time of decision making, chooses the next machine to be served by the robot. There are some very well known strategies, like the FIFO sequence introduced above, that looks appropriate for this type of problem. These strategies allows the robot to "improvise" (i.e. change) the sequence of machines when the regular current activity is altered due to machine assistance, being able to "immediately" serve a machine that re-enter in the line after assistance, so the main advantage is the capability of dealing with random perturbations. On the other hand, there is always a limit imposed by the fact that if two machines call the robot attendance almost at the same time the robot will move to serve one of them (call it m_j) and, in the meanwhile, the other (call it m_k) may finish the work and have some waste time. Considering that m_j and m_k become ready for reloading at the same time, there will be waste time if the working time of m_k is smaller than the time due to the following activities: finishing current loading

($\triangle t < t_{la}$ or $\triangle t < t_{lb}$), robot displacement from current position to m_j, loading m_j, robot displacement from m_j to m_k, loading m_k, and closing bridles in m_k, considering loading and processing times for the corresponding pallets, either A or B. The condition can be expressed as any of the combinations given by,

$$\left| \begin{matrix} t_{wa} \\ t_{wb} \end{matrix} \right| < \triangle t + \begin{pmatrix} t_{r1} \\ t_{r2} \\ t_{r3} \end{pmatrix} + \begin{pmatrix} t_{la} \\ t_{lb} \end{pmatrix} + \begin{pmatrix} t_{r1} \\ t_{r2} \\ t_{r3} \end{pmatrix} + \left| \begin{matrix} t_{lb} \\ t_{la} \end{matrix} \right| + \left| \begin{matrix} t_{cb} \\ t_{ca} \end{matrix} \right| \quad (11)$$

Values between parenthesis are independent with the unique constraint that t_{r3} cannot appear twice; values between bars have to be selected all from the top row or all from the bottom one. When the robot movement time is relevant with respect to the working time, inequality (11) can be satisfied if the robot serves first the closest machine, which is more likely to happen following a fixed sequence than FIFO. This effect can also appear when the machines do not call for the robot assistance exactly at the same time.

5.4 Effect of the Assistance to the Machines

When one of the machines requires assistance it is automatically disconnected from the manufacturing line until a human operator assists it, changes the corresponding tools, and put it on-line again. When a machine is in an assistance state the Robot Activity RA is reduced since both RM and RL are reduced, and therefore inequality (1) is more easily satisfied. Nevertheless, when the machine is put on-line it may have to wait for the robot to arrive to it, producing an undesired waste time that is different for fixed or variable feeding sequences. For a FM sequence it can happen that the machine gets into the line immediately after its nominal turn in the sequence, then it will have an unproductive time until the robot loads it again. It may be even worst with a FMFP sequence, if the machine gets into the line with the pallet that does not correspond to the sequence, the robot has to skip it and load it in the next cycle, although the machine is ready to work. For a FIFO sequence this effect is less relevant because, if necessary, the robot can load the machine that has just entered into the line before some others, but this strategy cannot avoid some waste time if one machine gets into the line exactly (or almost) synchronized with another one (effect described in Section 5.3). This undesirable effect can appear even when inequality (1) is satisfied. The machines request assistance randomly within a given period of time, so the exact influence on the different loading strategies requires an statistical analysis. A complete model for such analysis was not yet developed, but first results have shown that it affects more to fixed sequences than to variable sequences.

6 Summary

The problem of looking for optimum feeding sequences in a manufacturing cell with four parallel machines, each one working on two pallets, was presented. The problem was stated by a car-part manufacturing company, trying to avoid unproductive times of the machines. The cell was simulated and different feeding sequences were tested. The results show that the best way to serve the machines depends on the duration of the different actions in the cell, in particular, it is clear the relation between the time needed for the robot movements from one machine to another and the cycle working time of each machine. For the particular values given by the company, FIFO strategy gives a percentage of waste time of up to two orders of magnitude better than a FMFP sequence. Some reasoning about the problem was also included in the paper. The simulations allowed a good enough resolution of the real problem of the car-part manufacturing company, but the complete theoretical model of the cell with a function to easily determine the optimum feeding sequence is still an open problem.

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