MULTI-STAGE MANUFACTURING SEQUENCE MANAGEMENT

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Abstract

Mass production manufacturing requires the coordination of multiple component suppliers, their logistics processes and the final assembly facility. When the production sequence deviates from plan in facilities that produce large and expensive items, like automobiles, the disruption causes substantial additional costs. This paper explores the degree of sequence recovery that can be achieved in typical facilities using different local policies.

1 Introduction

Modern mass production manufacturing requires the synchronized production and delivery of multiple components and modules for the assembly of each finished product [1, 4]. This process requires the coordination of multiple suppliers, their logistics processes and the final assembly facility.

When a problem is detected with a product during the process, it is removed from the production process. The item is returned to the process when the defect is corrected. This delay causes the production sequence to be different to that originally planned and can result in substantial disruption in further stages of manufacturing to the affected item, and those before and after it.

If these delayed items can be restored to their correct position in the production sequence any impact can be avoided and the productivity of the overall facility maintained.

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While it is difficult to change the order in which a product is worked on during a process, it is often possible to carry out limited sequence recovery in storage areas between process stages. The storage areas are created because of a need to apply different kinds of processes and necessary transport between different areas of a production facility.

The amount of sequence recovery is limited by the size of the storage areas. A trade off must be made between the achievable improvement in sequence against the desire to minimize work in process.

The remainder of this paper discusses these concepts in the context of an automotive vehicle manufacturer.

2 Automotive vehicle manufacturing

Automotive manufacturing facilities are configured as a sequence of three major stages. These are: the body line where pressed steel components are welded into unpainted bodies, the paint line where protective and decorative coatings are applied to the bodies and the trim line where the vehicles are fitted with mechanical and trim components.

Figure 1 shows the structure of a typical manufacturer that produces three distinct types of vehicle bodies, uses a shared line to paint the vehicles and has two trim lines for the finishing processes.

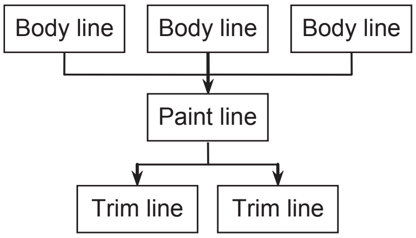

Figure 1: Multi-stage line relationships

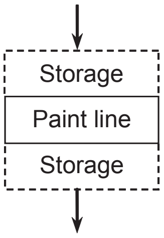

Figure 2: Paint line configuration

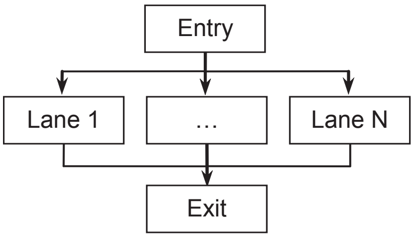

Figure 3: Multi-lane storage area

The paint line in the high-level diagram is shown in Figure 2 in more detail with a storage area shown before and after to balance transient performance deviations between the preceding and following processes.

These storage areas are often built using a number of identical sequential conveyors with common entry and exit areas[1] The diagram shown in Figure 3 shows the typical configuration of a storage area with N lanes. More sophisticated storage areas may contain additional paths that permit the movement of vehicles from the exit area back to the entry area to achieve more complex sequence recovery.

The policies used for loading and withdrawing vehicles control the degree to which the original desired sequence can be recovered.

This paper considers only a static sequence. Many researchers have investigated [5] dynamic sequence generation of vehicles actually present in the storage areas.

The following sections describe: the metric used to measure delay, the approach used to recover the original sequence, a number of entry and exit policies for a storage area and simulation results for a selection of policies.

3 Delay metric

Vehicles are scheduled to be manufactured in a sequence determined during the planning process [2]. A vehicle is considered to be produced in sequence if it is manufactured before any of the vehicles scheduled after it; otherwise it is considered delayed. The metric measures the proportion of vehicles that are not delayed.

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[1] In smaller volume facilities these storage areas are configured as random-access storage buffers. The sequence recovery policies in such cases are the optimal ones of selecting an empty bay on entry and selecting the correct vehicle on exit.

Provided that a large enough storage area is available with sufficient flexibility in changing the sequence of stored vehicles, any sequence with finite delays can be restored.

4 Sequence recovery approach

This section describes the approach used in selecting policies for sequence recovery. The requirements identified for the policies are:

- Only local knowledge required
- Limited complexity decision procedure
- Limited number of choices
- Robust to occasional decision error
- Not (very) dependent on existing buffer condition

These requirements consider a manufacturing facility that needs to manually implement the policies. They also recognize that the original sequence incorporates sophisticated planning decisions with knowledge of work content and supply chain restrictions that any approach can, at best, only attempt to recover the original sequence.

Sequence recovery is also a pragmatic best approach as the original sequence is one that will have been used for other planning activities and restoring this sequence will minimize communication and resynchronisation effort.

Limiting the sequence recovery approach to a simple split-merge multiple lane buffer provides a useful baseline case. The research can be extended to configurations that permit recycling from the exit to the entry area and where additional information on preferred sub-optimal sequences is available. The effectiveness of various policies is established by simulating their operation for input sequences with varying degrees of sequence disruption and comparing the results.

5 Policies

The identified policies control either the lane into which a vehicle is placed into the storage area, or the lane from which a vehicle is removed.

The number of lanes and the maximum length of the lanes determine the amount of sequence recovery possible. For example, if the storage area holds an average of k vehicles, then a vehicle delayed at most behind k others can be returned to its original location. Delays that are greater than k can not be fully recovered. The quantity chosen must be considered in conjunction with the desire to minimize the number of vehicles held in work in process.

For completeness, some policies are described that are not further considered as they are clearly less effective than the ones chosen. These were previously identified in the initial report [3].

Each policy is described with a decision procedure along with limitations or benefits that apply specifically to the policy.

Most of the policies are tolerant to occasional errors and will recover after the incorrectly processed vehicle has been withdrawn from the store.

5.1 Distributed entry

Vehicles are distributed evenly into storage lanes in sequence. If a lane is full, the lane is skipped. This policy is stressed by increasing delays and can at best restore delays that are smaller than the number of lanes in the store. It provides a useful bound on sequence recovery against store size.

This policy may result in lane overflow in cases of severe sequence disruption due to uneven withdrawal at exit.

The policy requires that the most recently used lane be remembered along with a full indicator for each lane. It can be implemented by human operators who are able to see the entry point of each of the lanes.

5.2 Distributed exit

The distributed exit policy selects vehicles from lanes in turn without regard for the incoming sequence. If a lane is empty, it is skipped.

If this policy is paired with the Distributed entry policy, the policy will retain the incoming sequence without change.

This policy requires that the most recently used lane be remembered and can be easily implemented by human operators that are able to see the empty status of each lane.

5.3 Wave entry, Wave exit, Random entry, Random exit

These policies describe naïve approaches that are sometimes used but cannot provide sequence improvements in all except exceptional cases. The Wave policies act on the same lane until it is either full or empty; the Random policies select a lane at random.

They can be implemented by human operators with only knowledge about the most recent lane.

When paired they will retain the incoming sequence without change. In all other cases they will introduce additional delays in the production process and are not considered further.

5.4 Minimum exit

The minimum exit policy is the optimal exit policy for sequence recovery with only local knowledge. It selects from the front of the lanes the vehicle that is the oldest in sequence.

This policy can be implemented by human operators if they have visible confirmation of the sequence of the first item in each lane. It can operate with any entry policy.

5.5 Minimum entry error

Select lane with minimum positive distance between new vehicle and the last vehicle in each lane. If none is positive, select the lane with minimum negative distance. Distance is measured as the difference between the planned sequence between the two vehicles.

This policy expedites delayed vehicles by selecting the lane that minimizes the shadowing by later vehicles in the sequence from all the available lanes.

It has the side effect of maximally expediting vehicles along otherwise empty lanes when the storage area is below capacity, and returning to this state after a period of stress.

6 Simulation results

The simulations used a bespoke simulator (source code is available on request) that generated a sequence from an entry area, with random selection of the first or second item from the source zone. These were then loaded onto one of four lanes, each with a capacity of six vehicles, using the entry policy and withdrawn using the exit policy. The difference in sequence compliance before and after the store determines the efficiency of the policies.

In cases where the arrival and withdrawal rates vary materially, the capacity and number of lanes can affect performance. Simulation runs that saturated a lane in the store were removed from the data.

The simulation was performed for three different choices of entry and exit policy: the baseline, **Linear**, case with no sequence recovery, the **Minimum exit** case where vehicles are entered into lanes in turn and extracted in minimum order and the **Minimum entry error** case where vehicles are entered into lanes with minimum error distance and extracted in minimum order.

The two non-trivial simulations are each shown in diagrams showing the state of the store before, and after, a number of vehicles are loaded into and withdrawn from the store. The sample data has an entry sequence compliance of 58.1%.

6.1 Linear

A linear store is used as the baseline case. No entry or exit policies are applicable with a single lane. The withdrawal sequence is unchanged and the withdrawal sequence compliance remains at 58.1%.

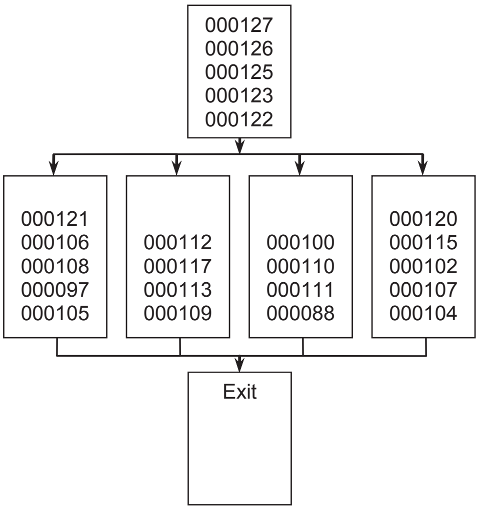

Figure 4: Minimum exit state

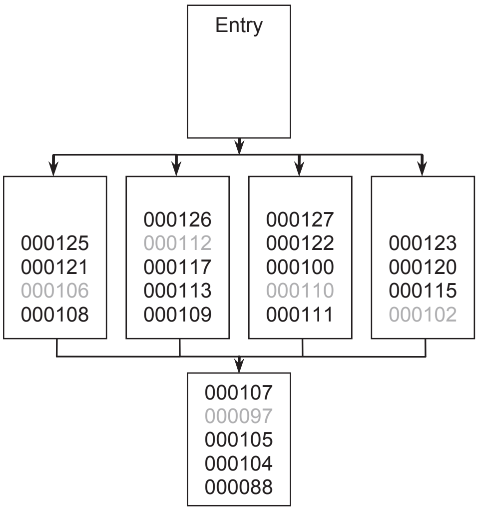

Figure 5: Minimum exit state after 5 further steps

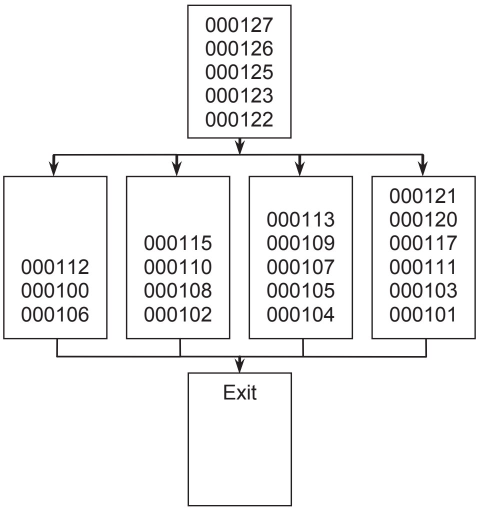

Figure 6: Minimum state

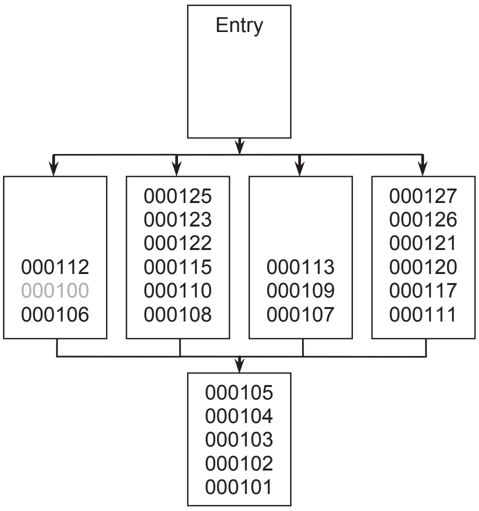

Figure 7: Minimum state after 5 further steps

6.2 Minimum exit

The state of the store is shown for the Minimum exit simulation in Figure 4 and Figure 5.

The second graphic shows the contents of the store and the exit area after a further five vehicles have been loaded into and withdrawn from the store. The sequence compliance rises to 74.3%.

In the fragment of the simulation shown, the exit area shows that one vehicle in five (shown in grey) has been withdrawn from the store out of the correct sequence. Further vehicles still in the store that will not be returned to their correct position in the sequence are also shown in grey.

The uneven withdrawal of vehicles from the store is also seen from the different quantities of vehicles in the different lanes. This could, in severe cases result in a lane being filled to capacity and preventing the Distributed entry policy from being directly applied.

6.3 Minimum

The state of the store is shown for the Minimum simulation in Figure 6 and Figure 7. Note that some lanes are full and require non-optimal placement on

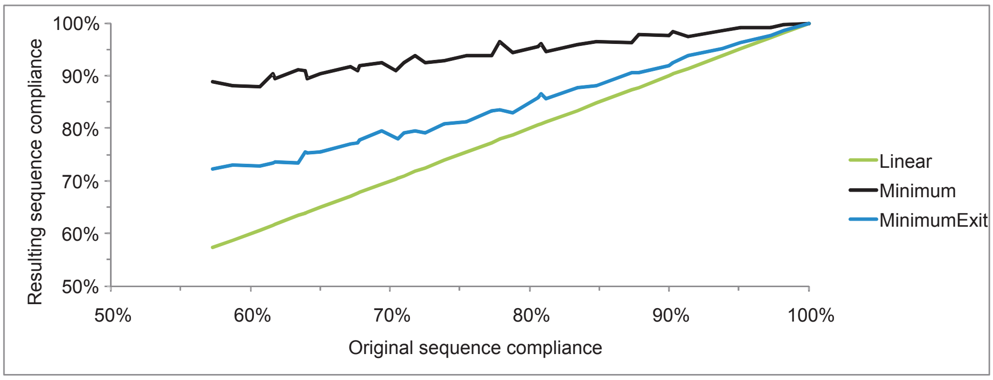

Figure 8: Sequence recovery efficiency over variable compliance rates

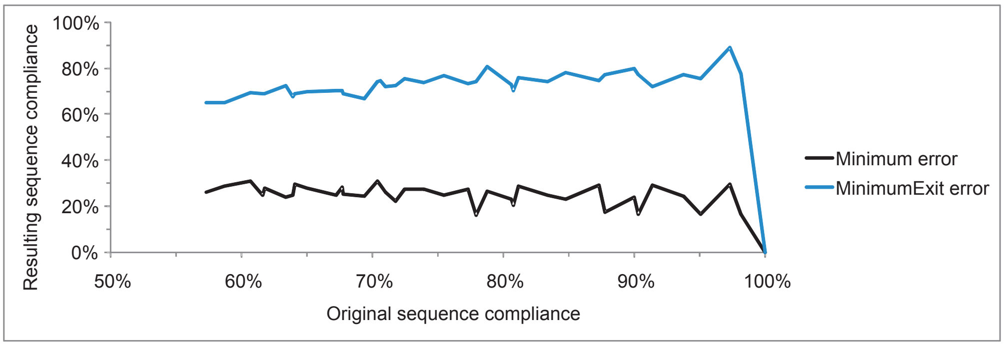

Figure 9: Sequence recovery remaining proportional error over variable compliance rates

entry. Only a single vehicle in the store will be withdrawn out of sequence. The resulting sequence compliance is 89.5%.

7 Simulation analysis

The chart in Figure 8 shows the sequence correctness rate for each of these three cases. The curve for the Linear case is a straight line, as expected with no sequence change, whereas the curves for the two other cases show clear increases in sequence recovery from the linear case.

The curves all converge to a resulting sequence compliance of 100% at the limit when the original sequence is in order. This suggests that the combinations of entry and exit policies chosen do not decrease sequence compliance for the in order case.

The results of the simulations show values without discontinuities suggesting the smooth behavior of the policies chosen.

In the two non-trivial cases an additional chart is presented in Figure 9 showing the remaining proportional error for different values in the original sequence compliance. This is the proportion of the original error that remains after sequence recovery.

This shows that the **Minimum exit** policy loses efficiency as the loaded sequence compliance improves, whereas the **Minimum** policy remains stable, or even improves with increasing input sequence compliance. Both policies converge as the loaded sequence approaches full compliance. This confirms the stability of the investigated policies across a broad range of sequence compliance rates.

8 Further work

Further investigation should be carried out with production data to compare the behavior of the simulations to actual behavior.

Within the constraints described in *Sequence recovery approach*, it is difficult to identify substantially better policies. If the use of non-local information is permitted, additional policies with better global characteristics can be easily identified.

9 Conclusions

A simple Distributed entry and Minimum exit policy can improve sequence compliance by about 10% while the more sophisticated Minimum error entry and Minimum exit policies result in greater than 20% compliance improvement. When sequence compliance is high ($> 90\%$) active sequence recovery can achieve compliance greater than 98% with local knowledge policies.

The selection of the Distributed entry and Minimum exit policies produces substantial compliance improvements. Since these policies can be implemented in a manual process, simple sequence recovery techniques can be used to improve sequence compliance in typical stores in the manufacture of automobiles.

A subsequent visit to a high-volume manufacturing facility confirmed the use of the Minimum error entry and Minimum exit policies in production.

References

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