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SIMULATION OPTIMIZATION OF PART INPUT SEQUENCE IN A FLEXIBLE MANUFACTURING SYSTEM

Howe Chiat Cheng

Republic Polytechnic
9 Woodlands Avenue 9
S(738964), SINGAPORE

David Yin Kai Chan

Advent2 Labs Consultation Pte. Ltd.
20 Kallang Avenue, Level 2, Pico Creative Centre
S(339411), SINGAPORE

ABSTRACT

This paper describes the development of a simulation model for production planning personnel to carry out optimization of part input sequence. The model simulates a flexible manufacturing system for the production of machined components. Using a custom built user interface, the planner imports production and demand data from an Excel spreadsheet into the model. The model optimizes part input sequence by simulating different combinations of part input sequences and determining the combination with the highest total slack time. Simulation conducted by the authors using this model shows that even a short, partial optimization run yields a schedule with improved slack. Presented in the paper are the steps involved in the development of the model and the benefits of the simulation-optimization model to the planner.

1 INTRODUCTION

Flexible manufacturing systems (FMS) are highly automated manufacturing systems that comprise computer numerical controlled (CNC) machines, an automated material handling system, a part fixture and storage system and human operator workstations. Due to a FMS's flexibility in processing a variety of parts simultaneously, production scheduling can be daunting and proper planning is necessary in achieving desirable operational efficiencies such as short production lead time, adaptability to changing customer needs and low inventory (Tempelmeier and Kuhn 1993). The research of FMS scheduling has generated much interests and many mathematical algorithms have been created for the scheduling problem. Most research focused on single objective optimization and dealt with specific FMS configurations (Udhayakumar and Kumanan 2010).

The inherent complexity, high investment cost and importance of scheduling in a FMS suggest that simulation can be a valuable tool. There have been many simulation studies done and recent ones include part launching and sequencing decisions (Joseph and Sridharan 2009), analysis of material handling system performance (Devikar et al. 2010), evaluation of tool assignment algorithms (Quiroga, Ciorciari and Rossetti 2007) and evaluation methodology of control strategies in FMS (Wadhwa, Singholi and Prakash 2009). Nevertheless, there is a sense that simulation has been under-utilized in manufacturing due to a number of factors (McLean and Leong 2001). For simulation to be a more readily accepted and useful tool, it will need to demonstrate greater real-time planning and scheduling capability to respond to the increasingly dynamic nature of manufacturing (Drake, Smith, and Peters 1995).

The study described in this paper is an endeavor at developing a simulation model as an efficient scheduler for optimizing part input sequence in a FMS. The model was built using Flexsim software (Flexsim Software Products, Inc. 2011) and has a user-interface (known as the Scheduler) that enables part and process data prepared in an Excel file to be imported into the model. OptQuest, the optimization module in Flexsim, is configured to run different sequences of part input and determine the sequence with the highest total slack. Using this simulation optimization method, the production planner is able to increase the efficiency of the order scheduling task. A 30-minute optimization run based on a 170-part order has shown that a potential improvement of 2.3% in total slack time can be achieved by implementing the new input sequence.

The paper is organized as follows: Section 2 describes the flexible manufacturing system in the study. Section 3 covers model building and assumptions. Section 4 presents the work on verification and validation. Section 5 describes the optimization process and results. Lastly, Section 6 provides concluding remarks for the study.

2 MANUFACTURING SYSTEM AND PROCESS OVERVIEW

The flexible manufacturing system (FMS) in the study consists of 6 CNC machines (known as machining centers or MCs), 1 coordinate measurement machine (CMM) and 2 work control stations (WCS) (Figure 1). There are several storage racks in the system, which store multi-faceted fixtures (MFF) used to hold parts in place during machining. An automated rail guided vehicle (RGV) facilitates the MFF movement between storage racks, work stations and machining centers. The turn tables automate the transfer of the MFF between the RGV and machining centers/ CMM/ WCS. Blank inspection and clean & press stations cannot be reached by the RGV. Operators carry the parts to these 2 stations.

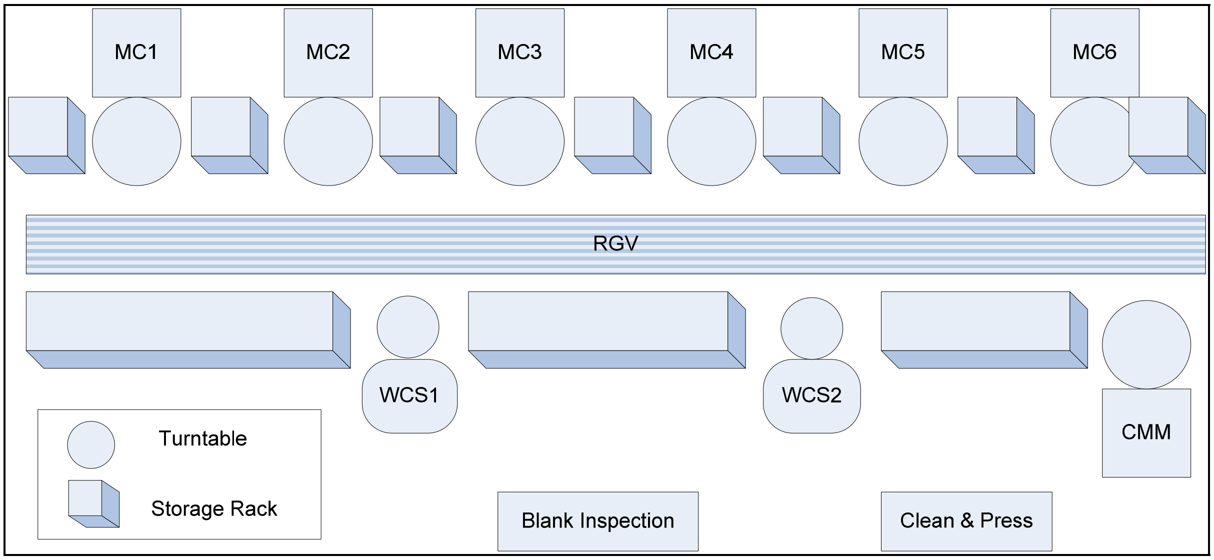


Figure 1: Layout of the Flexible Manufacturing System

Figure 2 shows the general flow of the manufacturing process. The process begins at one of the WCS with the fixing of a part onto a specific face of the MFF by the operator. He will activate the RGV to move the part to the first machine. Once the part is processed and exits from the machining center, the RGV returns it to the WCS and the operator will unload it from the MFF. The operator then fixes the part to another MFF according to assigned information for the next machining process. If the required machining center or WCS is not available, the MFF that contains the part will be sent to the storage rack to wait.

Parts are selected for CMM inspection according to a sampling plan. The selected parts are sent to the CMM after every machining process. If a part fails CMM inspection, it will be transported to the previous machining center and be re-machined. A blank inspection is carried out after every successful CMM inspection, upon unloading of the part from the MFF. Parts that fail the blank inspection are removed from the FMS and kept in view pending action by an engineer. Finally, a part may require clean & press after certain machining process.

Orders are received in batches indicating part number, quantity and due date. Lead time can range from 3 days (urgent request) to 3 months, though typically the duration is 1 week. The operational aim of the FMS is to complete existing orders within the shortest time in order to maximize the total slack time (slack time for each order = due time – actual completion time). It is not infrequent for customers to hand in urgent orders, in which case the challenge will be to complete them as soon as possible while meeting the due dates of the existing orders. Besides the dynamic nature of incoming orders, the FMS contains a number of complexities that makes part input scheduling a demanding task:

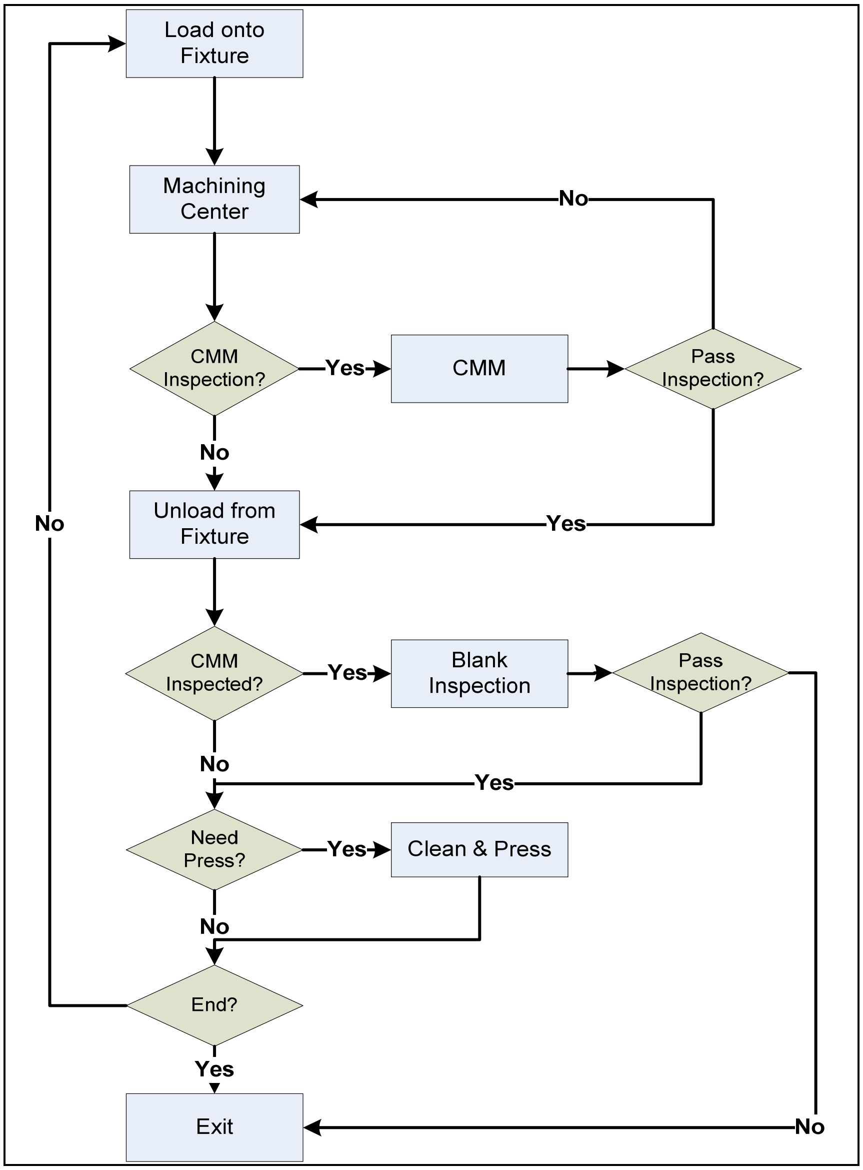


Figure 2: Part process flow of the Flexible Manufacturing System

1. The operator can launch the production of any new parts at any time, and will do so as long as the WCS and the required MFF are available.
2. Typically a part requires five to eight machining processes to complete production. Some parts take longer due to sampling inspection and the possibility of rework.
3. Whenever there are many in-process parts, the WCS naturally becomes the bottleneck. The parts waiting to enter the work station could be from one of the following: machining center, CMM,

clean/press process, blank inspection, or new part launch. It is difficult to plan a schedule with minimal waiting time due to the complex nature of the process flow.

4. Other parts of the FMS may also experience queuing. They include the MFF, RGV, machining center, CMM, blank inspection and press/clean station.

3 MODEL BUILDING

We built the FMS model using Flexsim simulation software. Flexsim offers a 3-D view for model building and animates the process flow, which is very useful when presenting the simulation model to the process owners. The layout and dimensions of the facility were created in an AutoCAD drawing. The drawing was imported into Flexsim and used to calibrate the model to scale. For example, the distance between any 2 machining centers as well as the movement speed of the operator and the RGV are accurately represented in the model.

From Flexsim's discrete object library, we picked suitable objects and customized their 3-D appearance to construct the FMS model shown in Figure 3. Global Tables are used extensively for data input and to keep track of part status during simulation. Additional programming using Flexscript (similar to C++ language) were carried out to incorporate the below algorithms into the model:

- Every part type has a unique production routing together with specific machining timings.
- Each MFF has a number of faces and each face can be fixed with a part. Before a part is sent to a machining center, it has to be loaded onto a particular face of an assigned MFF, and this information is pre-determined and dependent on the machining process.
- A MFF may be fixed with more than one part. If a MFF contains two or more parts, and their next process utilizes the same machining center, the parts will be processed consecutively in the machining center without having to unload one finished part from the MFF first.
- If a MFF that is fixed with a part/parts is available, it will be called upon to be loaded with a new part whenever possible.
- Priority of part entry into machining centers is based on first-come-first-served (FCFS) rule. For entry into the WCSs, waiting parts are accorded the following order: 1) parts returning from machining center or CMM to be unloaded, 2) new part launch, and 3) parts returning from clean & press or blank inspection to be loaded. If there are more than one part returning from the same process, the entry order is FCFS.
- The RGV operates on a FCFS basis with regard to parts waiting for transportation.

3.1 Assumptions

All process timings (machining, inspections, clean & press, loading, unloading and movement) take on constant values in the model. The assumption is that processing and transport time variations are small and does not influence the comparison of different input sequences. Another assumption is having a fixed CMM sampling plan and inspection pass rate as well as pre-determined periods of operator break and facility maintenance. Downtime from machine breakdown is not considered as the data is unavailable. Finally, for blank inspection rejection rate, historical records showed that the occurrence is random and infrequent. A small rejection rate is considered when validating the model. However, it is not applied in optimization runs as it will not affect the optimal sequence of part input.

4 VERIFICATION AND VALIDATION

The model was put through rigorous debugging. In order for the software to detect explicit errors in the model, all part types were included, each having an order quantity of three. Each time an error was uncovered and debugged, 10 simulation runs were subsequently made. Different input sequences were generated for the runs to increase debugging effectiveness. To ensure that there is no logic error, the movements of individual parts were observed through the entire process. In-process information were recorded and verified during the simulation.

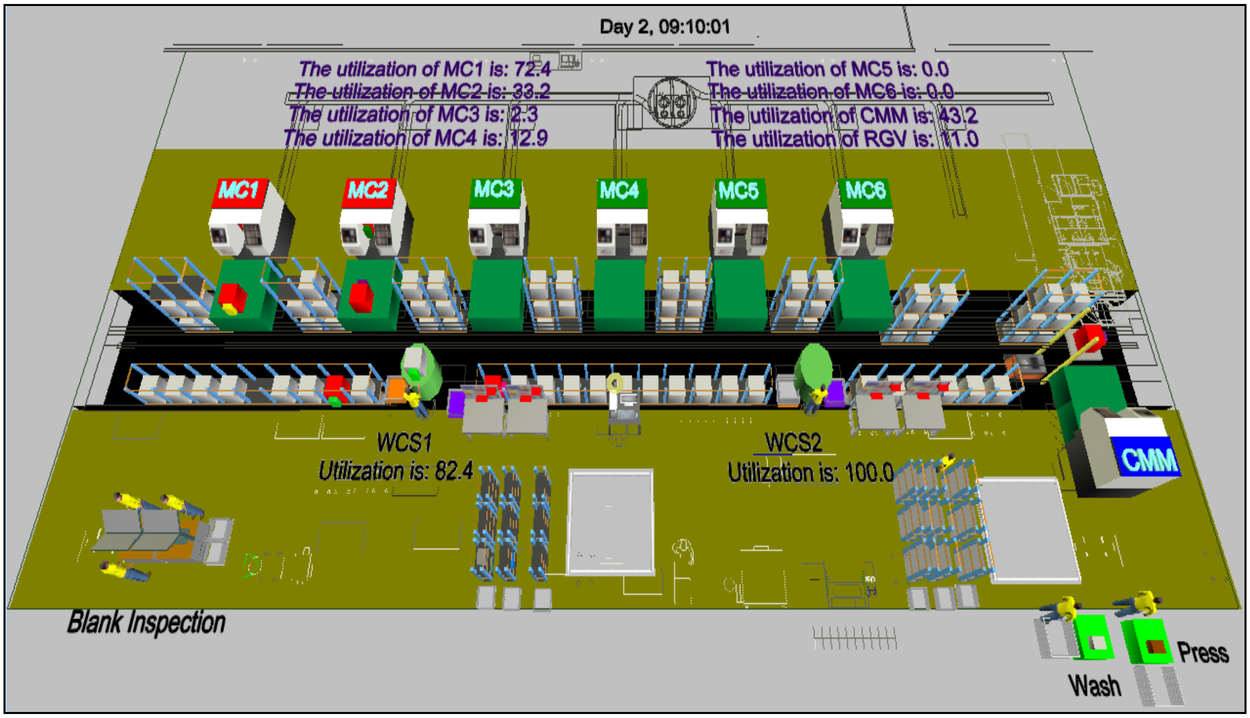


Figure 3: Flexsim simulation screenshot of the FMS model

Once we were satisfied with the model, the simulation was presented to the production supervisor and the main planner. Step-by-step simulation of the entire production process via 3-D animation enabled the audience to visualize the different parts of the FMS in the model, inspect the accuracy in the process flow and transport timings and understand how the assumptions affect the simulation. To validate the model, a 132-part historical order were used and the scenario simulated for 10 replications. The output of makespan as well as average utilizations were assessed to be acceptable to the process owners (Table 1).

Table 1: Simulation results for FMS performance

Makespan (minutes)	Average Utilization				Blank Inspection Reject
	Machining Centers	CMM	WCS	RGV	
4493.9 ± 144.7*	49.7%	18.5%	64.9%	12.7%	13.1%

*Makespan value indicates mean and 90% confidence interval; the others are mean

It was observed from the result that the deviation of the makespan values from the mean can be as large as 2.4 hours based on 90% confidence limits. There are 2 contributing factors to the variation: a) Random CMM inspection failures increase the makespan as a result of re-machining, b) A small probability of reject from blank inspection (once a part fails blank inspection, it exits the system). We also noted that there is a degree of negative correlation between makespan and the average utilization of the machines (Figure 4).

5 OPTIMIZATION

In current practice, the planner starts to prepare the Sequence of Order (SO) on the first work day of the week for the following week. The SO is subject to frequent changes from urgent orders and change orders. Throughout the week, the planner will attempt to reduce the completion time by adjusting the sequence according to his experience or by trial-and-error. The schedule is ready only at the end of the week. With the implementation of a user interface for data input (the Scheduler) and simulation optimization in Flexsim, the creation of SO takes about 1.5 hours. This greatly reduces the preparation time, giving the planner the option to work on the SO on the last work day of the week.

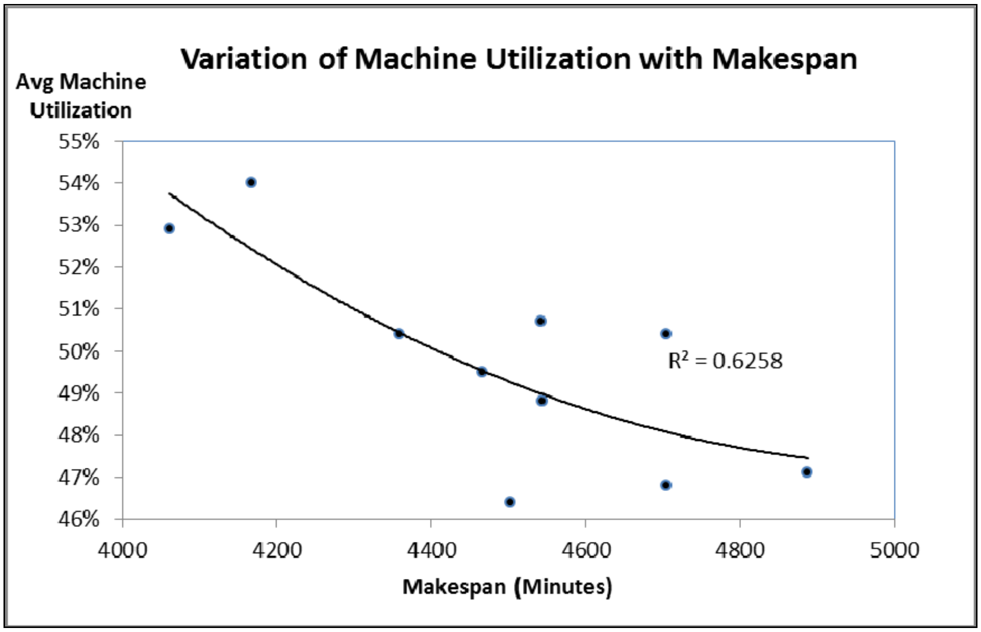


Figure 4: Validation results showing negative correlation between machine utilization and makespan

5.1 Workflow

Figure 5 illustrates the workflow from raw work order to the SO generated by the optimization. The preliminary input sequence to the model is a list of work orders generated through Master Scheduling. Each work order contains the part number, quantity required and due date. The planner will input the work order information into an Excel spreadsheet. A macro program is written to break down the orders into "one piece" orders. These data are then imported into the Flexsim model.

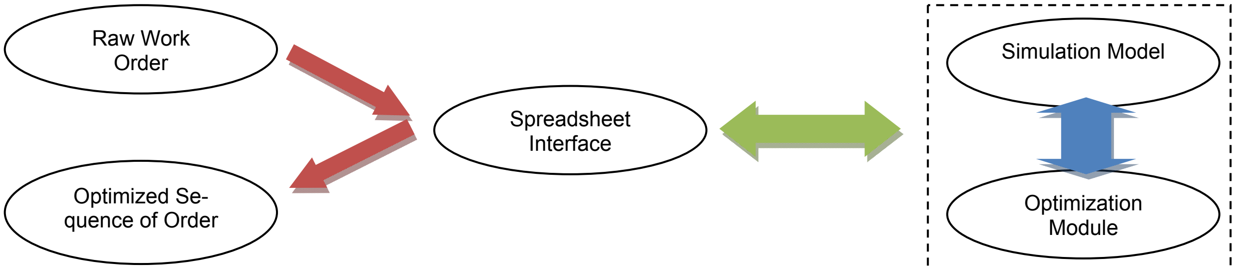


Figure 5: Data flow between work order and simulation optimization

When the production and order data are ready, the planner runs the optimization module (OptQuest) within Flexsim. In OptQuest, the sequence of each order is treated as a decision variable and the optimization engine attempts to maximize the total slack to achieve the optimal input sequence. Subsequently the result is exported back to the spreadsheet as Sequence of Order.

5.2 Optimization Function

The assumption in developing the objective function is that orders are to be scheduled and completed such that there is maximum total slack. Slack is defined as the difference between the due time and completion time for each work order, where when slack is positive, the order is early and when slack is negative, the order is late. Since all orders are in the FMS and ready for processing at time 0, maximizing total slack is the same as minimizing the average completion time or flow time.

Mathematically, let n be the order of work order where n is a positive integer number, T_d is the due time and T_c is the actual completion time. The slack for the n^{th} work order is: $Slack_n = (T_d - T_c)$, where n is $1, 2, 3...$

If the objective is to have a schedule where the total slack of work orders is as high as possible, the objective function is: $Maximize\ Total\ Slack = \sum^n (T_d - T_c)$, where n is $1, 2, 3...$

If it is desirable to ensure that the due time of work order i is met, the due time constraint for the work order can be added: $Slack_i > 0$

5.3 Optimization Result

The scenario used for our simulation optimization run is based on an order of 170 parts. The number of possible combinations of order input sequence is $170!/\Pi n_i!$, where n_i is the number of parts for part type i. The optimization program runs a different sequence in each scenario, so simulating all combinations of sequence is practically impossible. In our comparison study (results shown in Table 2, Figure 6 and 7), a 30-minute time frame was imposed on the optimization. A total of 20 scenarios for the 170-part work order were run. More runs should improve the slack time further.

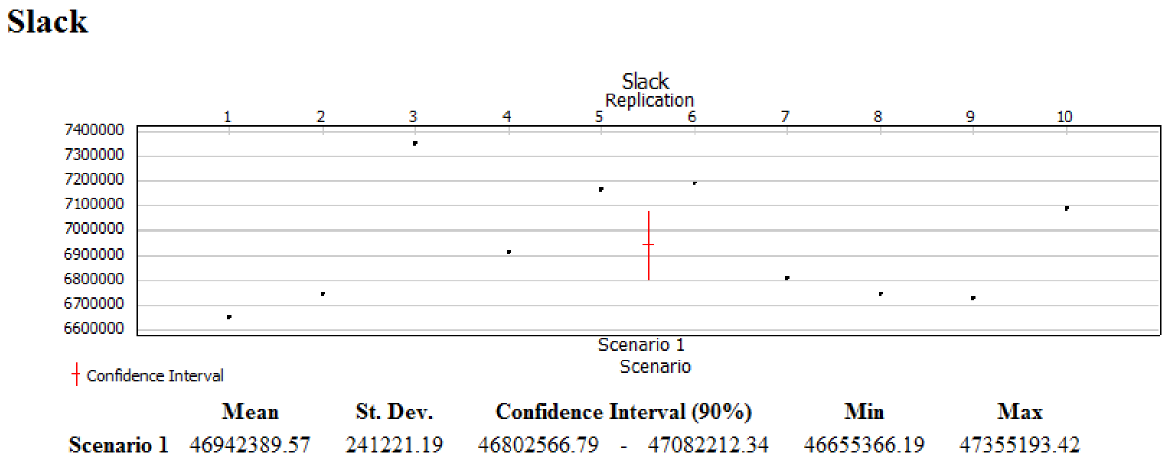
Table 2: Comparison of slack before and after optimization

	Before Optimization	After Optimization	Improvement	P-value for 2-Sample T-test
Average slack	543.3 days	556.0 days	12.7 days (2.34%)	~ 0
Standard deviation	2.79 days	2.10 days		

A 2-sample hypothesis T-test was performed to compare the slack time for the work order before (the actual historical SO) and after optimization. The slack improvement, though small in percentage terms, is statistically significant. The optimization is seeking the best non-delay schedule, which strictly speaking, may not be optimal but will be close to optimal most of the time (Askin and Standridge 1993).

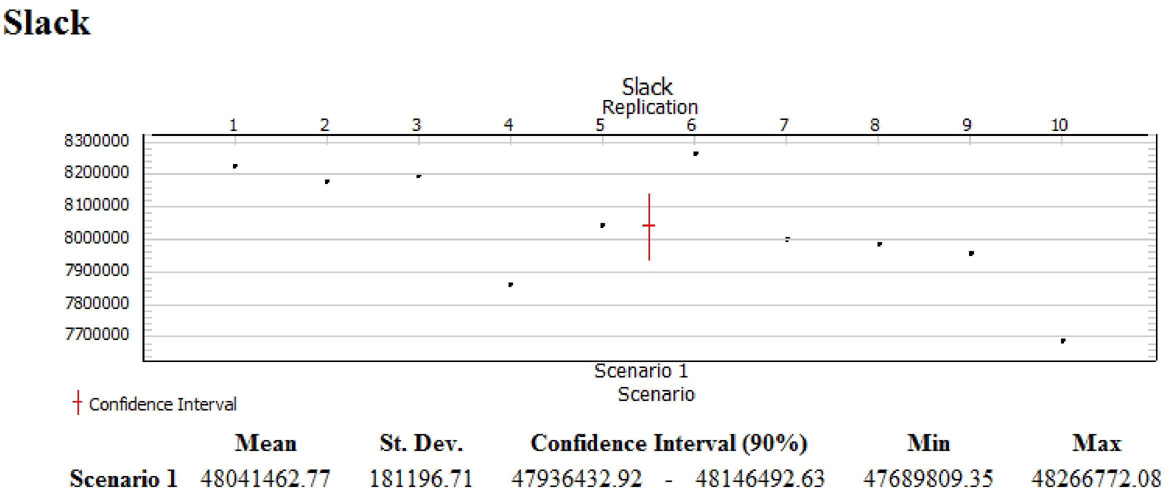
6 CONCLUSION

We presented a paper describing the development of a simulation model for a complex FMS. The simulation optimization approach optimizes the part input sequence by determining the sequence that has the highest total slack time. The variables in the simulation are the input sequence, the sampling rate for CMM inspection and the inspection fail rate. It is possible to study the effect of other factors such as material movement speed, machine breakdown and part dispatch rule on the FMS's performance. The use of the model and a customized user interface provides for more efficient production scheduling.


Slack

	Mean	St. Dev.	Confidence Interval (90%)	Min	Max
Scenario 1	46942389.57	241221.19	46802566.79 - 47082212.34	46655366.19	47355193.42

Figure 6: Flexsim results for slack before optimization (values shown in seconds)


Slack

	Mean	St. Dev.	Confidence Interval (90%)	Min	Max
Scenario 1	48041462.77	181196.71	47936432.92 - 48146492.63	47689809.35	48266772.08

Figure 7: Flexsim results for slack after optimization (values shown in seconds)

The current optimization method of simulating every sequence combination is time consuming, especially when the number of parts is high. No heuristic was used to minimize the number of runs in the study but it is possible to create constraints in the optimization to reduce the number of runs. For example, the orders can be pre-sorted in ascending order of the total run time. Constraints may be added such that the optimization engine does not consider scenarios where orders with the smallest total run time are late in the sequence. The constraints can be pre-programmed and initiated with the Scheduler interface.

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AUTHOR BIOGRAPHIES

HOWE CHIAT CHENG is a senior academic staff in Republic Polytechnic, Singapore and holds a Master of Science degree in Industrial and Systems Engineering from National University of Singapore. He develops and delivers academic curriculum in the areas of operations management, reliability engineering, manufacturing planning and other subjects in the realm of industrial and operations management. He frequently supervises simulation projects carried out for companies in the logistics and manufacturing industries. Prior to being an academic staff, he worked as an analyst in the defense industry building optimization and simulation models to determine logistics support requirements. His email address is cheng_howe_chiat@rp.edu.sg.

DAVID YIN KAI CHAN holds a Master degree of Engineering Science from University of New South Wales in Manufacturing Management, Bachelor of Engineering degree from National University of Singapore and Certificate in Production and Inventory Management (CPIM) by The Association of Operations Management. He is the Managing Consultant with Advent2 Labs since July 2001 and provides consultation in improving productivity and process re-engineering related project implementation. His clients include National Library Board, Wyeth Pharmaceutical, Hamilton Sundstrand, Siemens Material Handling, IMI (Philippines), Hewlett Packard and Singapore Institute of Manufacturing Technology. He is also currently an Academic Associate with Republic Polytechnic and a member of Institute of Engineers, Singapore, and Institute of Industrial Engineers, Singapore. His email address is chanyk@advent2labs.com.