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## Simulation-Based Decision Framework for Hybrid Layout Production Systems Under Disruptions

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### Abstract

In a hybrid layout production system under uncertainties, making strategic decisions becomes crucial and demanding, with an increase in the complexity of the system. The advent of Industry 4.0 leads to the development of technologies such as smart factories, simulation, cloud, cyber-physical systems that use digital twins for making informed strategic decisions in a factory. This paper proposes a decision-making framework for a multi-product hybrid layout production system under stochastic disruptions using a simulation model. The simulation model will act as a digital twin of the physical system, which helps to proactively visualize and analyze several key performance parameters of the system and make informed decisions. The objective of this paper is to identify the best sequence from predefined sequences for jobs, which maximize profit, throughput, and minimize cost, and make-span. Several experimentation cases are developed to analyze the performance of the system under different scenarios of disruptions and make strategic decisions such as investing in new machines, prioritizing products, and rescheduling of products.

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### 1. Introduction

**Emerging Trends and Challenges.** The advent of new-age technologies Internet of Things (IoT), Cloud, Simulation, Autonomous Robots, System Integration, Cybersecurity, Additive Manufacturing, Data and Analytics, and Augmented Reality has led to the formation of “smart factories.” The integration of the above technologies is referred to as Industry 4.0, where humans, systems, and machines exchange information using network devices and sensors for coordinating and monitoring the processes in the industry.

Digital twins can make dynamic changes to the system in real-time based on changes in the physical system. Simulation plays an important role in the design of a digital twin of its physical counterpart and making decisions on the current

system or for making improvements while creating future systems. The simulation data can be used as a baseline for these decisions and determine the key aspects of the system to understand its operations. The simulation also provides important insights into the physical model when working under extreme conditions. It helps the user to make decisions to tackle the obstacles without affecting the performance of the physical system.

**State of the art.** Simulation has been widely used for making decisions in manufacturing industries for long, and it helps in making critical decisions on job scheduling, investment on machines, operators, purchasing, etc. These are NP-hard problems requiring complex computations for determining the

strategic decisions and optimize the performance of the system. There are factors such as stochastic disruptions, the layout of the facility, demand, service level required, the arrival rate of materials, processing cost, etc., which influence the performance of the system significantly. Using digital twin to simulate such models helps to make these decisions real-time or near real-time to improve their performance. Uncertain conditions in the process create plenty of hardships in various aspects such as resource allocation, job scheduling, operator assignment, etc. as the system becomes highly unpredictable.

Machine breakdowns are a significant type of uncertainty in the manufacturing process, and it can be either predetermined or stochastic. Predetermined disruptions are those planned temporary stoppage of machines for maintenance, tool change, shift change, etc.. In contrast, stochastic disruptions are unforeseen events of disruptions due to power failure, tool breakdown, machine damage, or other unexpected breakdowns. Such conditions require critical decisions such that normal working conditions of the entire process are least affected by the disruption. This is referred to as the resilience of the system, and the higher the resilience of the system, the higher performance of the system, and it will be capable of accommodating sudden changes in system parameters.

Simulation of such unprecedented events helps managers to make crucial decisions by anticipating unsolicited events. Manufacturing industries adopt layout configurations based on criteria such as distance traveled, flow volumes, and several cost criteria including purchasing, installing, maintaining machines, and material handling systems. Based on different criteria, several layouts, such as product layout, process layout, functional layout, cellular layout, and fixed layout, etc. are being used in industries. These layouts are considered traditional layouts are focusing on a single part or part family, multiple parts with the same processes. In contrast, currently, industries implement a combination of these layouts called as non-traditional layouts. The hybrid layout production system is a combination of cellular layout and functional layouts, which contains multiple replicates of machines, but not all machines are identical [1].

The flexibility and flow volume of the layout depends on the degree of replication. This type of layout is commonly adopted by process industries and some flexible systems processing non-family parts distinguish hybrid layout from the cellular layout. The cellular layout consists of cells capable of machining part families, whereas hybrid layout can process jobs not in a part family along with the part families.

**Research Contribution.** The performance of a system under disruption needs to be studied and researched in detail. The simulation gives real-time data of a digital twin of the hybrid system under stochastic disruptions and based on this data; it helps to make crucial decisions in the original system.

**Paper Organization.** The remainder of the paper is organized as follows: Section II provides the review of related work regarding various simulation modelling methods. Section III provides the proposed methodology for simulation modelling. Section IV presents a case study for demonstrating the proposed method, results and discussion in section V followed by concluding remarks and future work in Section VI.

## 2. Related Work

Job scheduling problems are those problems for determining a sequence or order of assigning machines for doing a certain job in a production system such that the performance of the system is optimum or near optimum. They are considered as Non-deterministic Polynomial-time hardness problem or NP-Hard problem due to the high computational time required for solving such problems. Zhang [2] reviewed job scheduling problems and its perspectives under Industry 4.0. Different approaches have been used for solving such scheduling problems. They are broadly classified into Analytical approaches and graphical approaches. Analytical approaches include mathematical models, heuristics, and meta-heuristics for objective parameters such as minimizing makespan, cost, Work-in-Progress (WIP), etc. The graphical approach uses Gantt charts, simulation, etc.

A two-stage hybrid flow shop problem is empirically evaluated to minimize makespan using a heuristic algorithm by [3]. The paper assumes replicates of machines at each stage and found that makespan increase with the increase in job arrivals. They used FORTRAN to solve the problem using the proposed algorithm. Ruiz [4] considered a problem of two-stage with identical machines in the first stage and single machine in the second stage to minimize makespan. They used branch and bound, and heuristics to construct an algorithm producing optimal and near-optimal solutions. The paper proposes a larger and complex problem scenario for future work. The inclusion of other performance parameters such as maximum delay, cost, etc. are also topics for further research.

Simulation modelling was used by Eric and Wade [5] in their paper for dynamic job shop rescheduling with machine availability constraints due to breakdown or maintenance. The sensitivity of rules was analyzed towards changes in breakdown rates, processing time distributions, and AGV priority schemes for Flexible Manufacturing Systems (FMS) [6]. Mean flow time was considered as the objective function against the scheduling rules of machines and AGVs.

A preventive maintenance breakdown (PMBD) heuristic was developed using the AWESIM modelling tool, and a visually interactive simulation model is created. Heng [7] developed an expert simulation system incorporating simulation technique, artificial neural network, dispatching, and expert knowledge rules for job shop rescheduling subjected to incorrect work, machine breakdowns, rework, and rush orders. They used Foxpro 5.0 and Matlab 4.0 to create the simulation model and fuzzy network. Girish and Nallan [8] compared the hybrid cellular manufacturing (CM) system with functional layout under different operating conditions to investigate performance measures such as flow time, work-in-process inventory, flow ratio, and machine utilization.

Factors studied comprise a system, setup factor, degree of part family similarities, lot size, and scheduling rule. Scheduling rules which are part family-oriented outperforms job shop rules. Li and shaw [5] proposed a neural network model and algorithm for hybrid flow shop scheduling in a dynamic scenario. They used simulation with a neural network to investigate the performance of dispatching rules. The training method of the neural network is optimized using the delta-bar-delta (DBD) method for faster training convergence. The simulation showed a neural network approach to be more effective than traditional dispatching rules. Other than dynamic job arrivals, including a machine breakdown, order

cancellation, and rush orders have scope for future work. Expected makespan and expected mean tardiness are minimized by integrating simulation into the genetic algorithm by [9]. They included stochastic unavailability due to breakdowns or due to scheduled preventive maintenance. They used a right-shift heuristic approach and event-driven policy in the algorithm to evaluate expected makespan and expected mean tardiness values.

Using random arrival times, other distributions for a time active, and time to repair for machines have scope for future research. Simulation is used to analyze the performance of different layouts under stochastic conditions by [9]. Performance of Distributed plan with minimum-part-order splitting (DL-MOS) is compared with process layouts with objective functions work-in-process, material handling cost, and cycle time. DL-MOS outperformed process layout in material handling cost, makespan, and WIP. Manufacturing systems subjected to perturbations such as machine failures, queuing techniques, and dynamic product route change based on availability may show variations in performance due to uncertainties. Hence, a detailed study is suggested as future research.

Mirabi [10] proposed a heuristic algorithm for minimizing the makespan of a two-stage hybrid flow shop with optimal job combinations and job schedules under breakdown conditions. The paper suggests increasing the complexity of the problem for future research and increasing the number of machines in the first stage. Zhe and Xingsheng [11] use an artificial bee colony (IDABC) algorithm for minimizing makespan for the HFS problem using vector representation. It integrates differential evolution and variable neighborhood search for generating new solutions. Studying the interaction between parameters with stochasticity and multi-objective scheduling cases are suggested for future work. Productivity and queue factors of the two production systems are compared. Prioritizing products, adding stochasticity, increasing the scale of the problem, etc. are areas for future work.

Two new heuristics were proposed using the critical ratio of allowance of setup and time to process in scheduling horizon. A simulation-optimization approach is used by [12] for HFSSP for minimizing flow time. The genetic algorithm is used for optimizing the strategy adopted for scheduling at different demand, product mix, and lot sizing levels. Chen and Theodore [12] investigate offline and online scheduling problems in JSS. They used a simulation modelling tool with JSS under dynamic and static problem settings.

Mohammed and Thomas [13] developed the Iterative Optimization-based Simulation (IOS) model for evaluating the performance of optimizers. They proposed a CallMATLAB step instance for integrating computational resources to the simulation package SIMIO to embed optimization techniques in simulation. A mixed-integer programming (MIP) model is proposed for a two-stage HFS scheduling problem with dedicated machines, sequence-dependent family setup times, and time lags to minimize makespan by Harbaoui [14].

A genetic algorithm is combined with the MIP for solving the problem and tested it on multiple parallel identical machines in the second stage. In the reviewed papers, the objective functions considered are mainly makespan, tardiness, WIP, single objective in most cases. In contrast, detailed investigations on other parameters of interests such as cost, profit, throughput, and material handling are limited. Most of

papers show that rescheduling of jobs under stochastic conditions affect the performance of a system under normal circumstances. A general framework for rescheduling assignments under stochasticity is not present, and it is essential to do a detailed study from a managerial perspective considering these aspects.

### 3. Methodology

In this section, a detailed description of the problem is given along with the assumptions and methodology adopted for creating the simulation model for experimental analysis. Production systems are subjected to several uncertainties due to factors such as variation in demand, arrival rate, processing times, disruptions, etc. The inclusion of these uncertainties in a digital twin is essential to make the production system model realistic.

In this paper, a multi-product hybrid layout production system subjected to machine disruption is investigated using a simulation model. The production system performance is affected by perturbations, and output parameters may vary based on the severity and frequency of disruptions. Crucial informed, proactive decisions need to be made based on available information and analysis to reduce the impact of disruption on the average performance of the system.

A simulation modeling approach is used to create a decision-making framework to visualize the real system and gather insights on the performance of the system under various conditions, which aid to make managerial decisions such as rescheduling based on cost and makespan, prioritizing of products based on profit, and investing in new machines. The simulation model will serve as a digital twin, which gives real-time visual feedback of the production floor and let the users analyze, interpret, plan, or make real-time decisions based on the variations in different factors that affect the performance of the process.

This paper aims to identify the best sequence for randomly arriving jobs from a set of predefined sequences for each job type under disruption scenarios with objectives of minimizing cost, makespan, and maximizing profit and throughput. Determining the balking condition in the input buffer at each machine and decision on investment on new machines are the secondary objectives in this paper. Machine utilization is considered when analyzing the performance of the process to make decisions on the addition of new machines or removing under-utilized machines.

The first part of this research involved the creation of a hybrid layout production system model using SIMIO with multiple products, which are assigned predefined primary sequences and alternate sequences as shown in Figure 1. A model framework of a production system with six machines is considered as the initial model. Machines are considered as servers in Simio, and six servers are created with paths interconnecting all the servers, source, and sink. Source and sink respectively act as starting and endpoints for the parts arriving in the system. Parts or products are created using entities, and for this model, eight products are considered, and eight entities are created with different colors to distinguish each part type.

User Defined processes in SIMIO, custom logic such as rescheduling an entity when a machine undergoes disruption

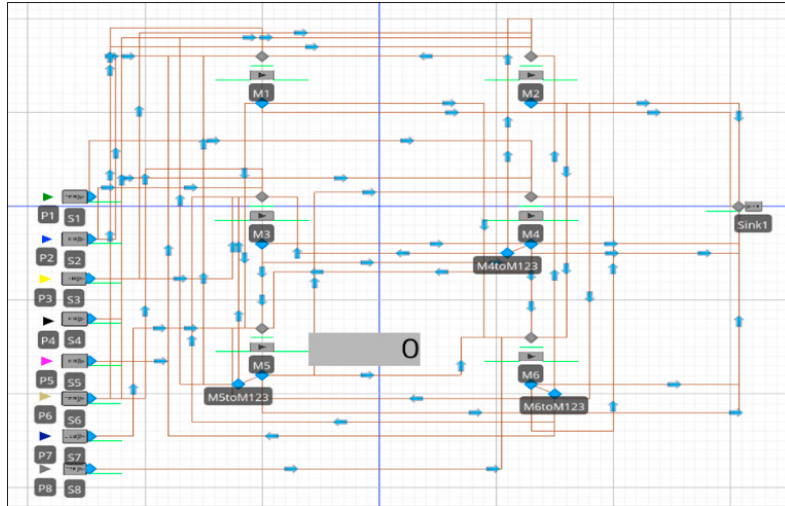


Figure 1: Simulation model using SIMIO

are designed, and the behavior of entities during disruptions are also explained. For making the model practical, stochasticity is used for part arrival, processing times, disruption frequency, and repair time. Processing times follow the random triangular distribution, and they are sequence and part type dependent. Part arrivals are based on random Poisson distributions of inter-arrival time, and each part type is assigned a fixed selling price. A hybrid layout with six machines is selected with three machines capable of carrying out the same process with different processing time and cost. For the three machines  $M_1$ ,  $M_2$ ,  $M_3$ , the cost of machining is assumed to be different such that they are prioritized based on cost. Multiple part types are considered for this research, each part type with three alternate sequences with the least cost sequence as the primary sequence. When a machine undergoes disruption, the parts arriving is assigned to the next best sequence from the predetermined sequences. The second phase of this research involves extensive experimental analysis by developing different cases of simulation under different levels of input parameters such as number of machines under disruption, disruption frequencies, number of alternate sequences, number of products, for making informed managerial decisions for minimizing cost, makespan or maximizing profit and throughput.

3.2 Assumptions:

1. Parts arrive in single units for a part type  
Unit parts arrive following a random Poisson distribution
2. Disruption occurs at intervals of random exponential distribution of processing time
3. Infinite buffer capacity at each machine
4. FIFO queuing policy
5. Processing time is the sum of setup, processing, and tear-down time

3.3 Formulation

- $P_i$  – Part types
- $M_j$  – Machine number
- $T_{i,j}$  – Processing time of  $P_i$  in  $M_j$
- $C_j$  – Cost of processing per minute in  $M_j$
- $S_i$  – Selling price of  $P_i$

Processing Cost for part  $P_i = \sum (C_j \times T_{i,j})$ , and the makespan of part  $P_i = \sum T_{i,j}$ . The initial model consists of eight distinct part types with different arrival rates. An arrival table with arrival rates following random Poisson distribution is created for each part type to integrate stochasticity in the model.

4. Implementation

The simulation model acts as a digital twin for the production system with a hybrid layout and processing multiple products. This section describes cases developed for experimental analysis for determining the performance of the model under different working conditions at different levels of the parameters - disruption frequency, product variety, buffer limit condition for balking.

4.1 Case Definition

For verifying the performance of the model as a decision-making framework for informed managerial decisions such as capital investment on new machines, assigning alternate sequences for jobs, determining product priority to increase profit, etc., different cases are developed for analyzing and comparing the results to make significant insights. Table 1 shows the different cases designed for experimental analysis.

Table 1: Case study model

Case Number	Machines undergoing disruption
Case 1	No Disruption
Case 2	$M_1$
Case 3	$M_1, M_3$

4.2 Case study 1

Case study 1 is the initial model created with all the machines assumed to be available for processing throughout the simulation span. The simulation is run for fourteen days, with eight product types having arrival rates, as mentioned. All part types follow their primary part sequence with minimum cost. Assuming event-based rescheduling, there is no rescheduling of products in this case as there are no disruptions of machines and thereby no unavailability of machines. The results are

expected to give maximum throughput and profit at the minimum cost compared to cases with disruptions. The buffer quantity at individual machines is expected to be minimum, and machine utilization is such that all machines are utilized with the capacity to incorporate additional load. The result of this ideal case will be used as a benchmark for comparing the results obtained from cases with disruption.

**4.3 Case study 2**

This case assumes the system is subjected to minor disruption. For that, M<sub>1</sub>, considered to be the least expensive machine, undergoes breakdown. Disruption frequency depends on the processing time between failures. Disruption frequency follows a random exponential distribution as it gives distribution closer to realistic values for the frequency of disruptions.

The cases are then run in two scenarios – first scenario, 2(a), assumes only one sequence for products, and they are not rescheduled in case of disruption, the second scenario, 2(b) uses alternate sequence when M<sub>1</sub> is disrupted. When disruption occurs in the second scenario, products are already waiting in buffer, and the machine remains until the machine becomes active. Products waiting to be routed to M<sub>1</sub> are rescheduled to their secondary sequence, which will have higher processing costs. The utilization of M<sub>1</sub> is expected to decrease as time available for processing during the simulation run decreases due to disruption, and products are rescheduled to the next available machine. The utilization of M<sub>2</sub> and M<sub>3</sub> is expected to increase as the parts are rescheduled. The cost of machining and makespan is also likely to increase for rescheduled parts.

**5. Results & Discussion**

Simulation identifies the best sequence from the available alternate sequences. Following sections describe results obtained after simulating different cases.

**5.1 Case 1:**

For comparing the performance of various scenarios of disruption, such as several machines undergoing disruption, machine disruption frequency levels, an ideal scenario is required in which machines are assumed to be available throughout the simulation run time. Case-1 implies machines do not undergo disruptions, and the system will be working at minimum cost sequences and maximum throughput. The Tables 2, 3, 4 & 5 show different performance parameters of the system, such as machine utilization percentage, cost of machining, throughput, and revenue. Total revenue, cost, and throughput are shown, and remaining cases aims to minimize the effect of disruptions on these parameters.

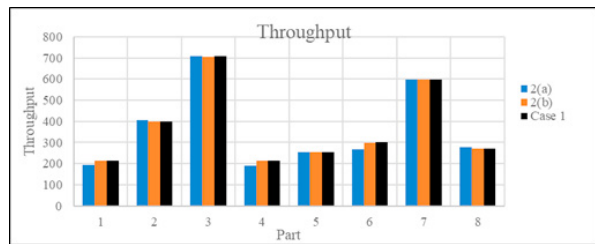
**Table 2: Machine Utilization and Cost of Machining**

Machines	Machine Utilization (%)	Cost of Machining (\$)
M1	99.5	6021.6
M2	75.2	9104.5
M3	73.6	5938.8
M4	75.9	4594.3
M5	93.2	7520.0
M6	99.5	10031.3
<b>Total</b>		43210.5

**Table 3: Cost /unit, makespan, revenue and throughput**

Part	Cost Unit (\$)	Makespan (min)	Revenue (\$)	Throughput (units)
P1	22.50	8.09	6450	215
P2	19.90	3.53	10400	400
P3	8.40	0.38	10605	707
P4	12.00	4.76	3870	215
P5	23.40	1.08	7936	256
P6	6.00	4.55	3600	300
P7	16.00	0.95	11940	597
P8	16.00	3.21	6006	273

**5.2 Case 2:**



**Figure 2: Revenue vs. part type**

In this case, the system is assumed to undergo disruption to the exponential distribution of processing time of a machine between failures. The disruption is restricted to the only M<sub>1</sub> in this case. The simulation is run in two different scenarios of using only one sequence and two sequences when disruption occurs. As the rescheduling of jobs is event-based, rescheduling only occurs when disruption occurs.

Hence when M<sub>1</sub> undergoes disruption, case - 2(a) assumes only one sequence. As a result, the makespan of the products is expected to increase with the increase in the number of jobs in the input buffer of the disrupted machine. In case -2(b), two sequences are used, and products use the second sequence when M<sub>1</sub> is disrupted.

**Table 4: Machine utilization and cost of machining**

	Machine Utilization (%)			Cost of Machining (\$)		
	Case 1	Case 2		Case 1	Case 2	
		2(a)	2(b)		2(a)	2(b)
M1	99.5	88.5	88.5	6021.6	5357.6	5352.9
M2	75.2	75.2	77.1	9104.5	9104.5	9325.4
M3	73.6	73.6	80.5	5938.8	5938.8	6498.8
M4	75.9	75.9	75.9	4594.3	4594.3	4594.3
M5	93.2	93.2	93.2	7520.0	7520.0	7520.0
M6	99.5	98.3	99.5	10031.3	9911.8	10031.3

The cost of machining increases, and makespan decreases compared to using only one sequence. As a result, throughput and revenue increase when using an alternate sequence. The values show that cost and throughput are closer to the ideal case when using two sequences when M<sub>1</sub> is under disruption. The utilization of machines M<sub>2</sub> and M<sub>3</sub> increases as more products are scheduled to these machines under disruption.

M1 utilization reduces to 88.58% and 88.51% in 2(a) and 2(b), respectively, from 99.56% in an ideal case as the machine is subjected to disruption and is not available during the simulation.

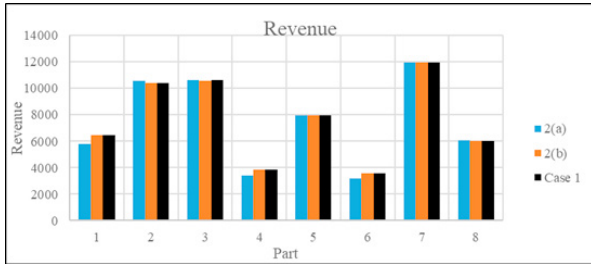


Figure 3: Revenue vs. part type

The utilization of machines M<sub>2</sub> and M<sub>3</sub> increases as more products are scheduled to these machines under disruption. M<sub>1</sub> utilization reduces to 88.58% and 88.51% in 2(a) and 2(b), respectively, from 99.56% in the ideal case as the machine is subjected to disruption and is not available during this span of simulation. Other machine utilizations remain nearly the same as in the ideal case as there is no change in the number of jobs assigned for machining. Figures 2 & 3 shows the graphical representation of revenue, and throughput respectively.

Table 5: Cost /unit, makespan, revenue and throughput

Part	Cost Unit (\$)		Makespan (min)		Revenue (\$)		Throughput (units)	
	2a	2b	2a	2b	2a	2b	2a	2b
P1	22	22	24	8.0	5790	6450	193	215
P2	19	19	1.4	3.5	10556	10400	406	400
P3	8.4	8.4	0.3	0.5	10605	10575	707	705
P4	12	12	23	4.7	3438	3870	191	215
P5	23	23	1.0	1.0	7936	7936	256	256
P6	6.0	6.1	22	4.5	3204	3588	267	299
P7	16	16	0.9	0.9	11940	11940	597	597
P8	16	16	1.1	3.2	6094	6006	277	273

Table 6: Total cost, total throughput, and overall profit

Case No:	Revenue (\$)	Throughput (units)	Profit (\$)
Case 1	60807	2963	17596
2(a)	59563	2894	17136
2(b)	60765	2960	17442

Table 6 shows that under disruption, two sequences increases the throughput and profit with compromise in cost as the total cost is found to increase. The single sequence will build up a buffer at the disrupted machine with reduced throughput and profit. Two sequence performance is much closer to the ideal case of no disruption. Figures 4 & 5 shows the graphical representation of revenue, and throughput. The utilization of M<sub>1</sub> and M<sub>3</sub> from the results show that alternate sequences can be used, and the system can incorporate perturbations.

5.3 Case 3:

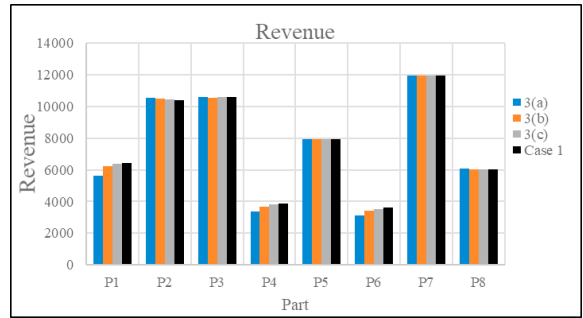


Figure 4: Revenue vs. part type

In case 3, the impact of disruption on the system is increased by assuming two machines undergoing disruptions with the same number of products. Machines M<sub>1</sub> and M<sub>3</sub> are the machines expected to experience disruptions, and the case assumes three sequences are available for the jobs for rescheduling under disruption. When there is no disruption, products will be scheduled in the primary sequence, and when one machine undergoes disruption, the product is assigned to a secondary sequence. If two machines are disrupted simultaneously, products are scheduled for a third sequence.

The simulation is run for fourteen days, and results are shown in the Table 7. Machine utilization, as expected, reduces when using the only single sequence as fewer number of products are machined in M<sub>1</sub> due to disruption. The utilization of M<sub>2</sub> and M<sub>3</sub> increases as more products are assigned to these machines under disruption, and M<sub>1</sub> disruption frequency is much higher compared to M<sub>3</sub>. Remaining machine utilization remains the same except for M<sub>6</sub> as the throughput of parts machined from M<sub>1</sub> to M<sub>6</sub> decreases.

Table 7: Machine utilization and cost of machining

Part	Machine Utilization (%)				Cost of Machining (\$)			
	Case	Case 3			case	Case 3		
		3a	3b	3c		3a	3b	3c
M1	99.5	86.2	89.1	87.2	6021.6	5217.8	5391.9	5274.8
M2	75.3	75.2	79.0	80.0	9104.4	9104.4	9558.0	9685.3
M3	73.7	73.6	75.6	77.4	5938.8	5938.8	6100.8	6241.6
M4	75.8	75.9	75.9	75.9	4594.2	4594.3	4594.3	4594.3
M5	93.3	93.2	93.2	93.2	7520.0	7520.0	7520.0	7520.0
M6	99.5	97.6	99.3	99.3	10031.3	9846.0	10014.3	10010.2
<b>Total</b>					43210.5	42221.4	43179.3	43326.2

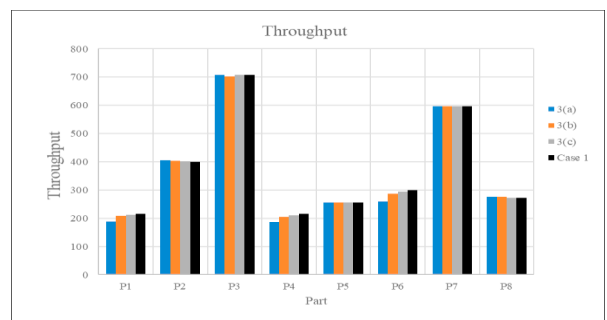


Figure 5: Revenue vs. part type

## 6. Conclusion and Future Work

A decision framework for a multi-product hybrid layout production system under real-time random disruptions using simulation models is created. The simulation model generates schedules for parts arriving randomly from predetermined schedules. Various cases are developed with different disruption conditions to verify the robustness of the model and for making informed managerial decisions in product prioritization, product routing, scheduled utilization of machines, capital investment in machines, etc.

Initial case studies show that the model selects product routes from a predetermined schedule according to actual parameter processing cost considering profit, makespan, and throughput. Disruption reduces throughput and profit, whereas cost, and makespan increases. As expected, the system performance varies when using a different number of alternate sequences. The initial phase of the thesis uses eight products, fixed frequency level of disruption, and infinite buffer capacity. Further insights can be determined on the performance of the system by increasing the number of products. The increasing frequency level of disruption also lets the users make decisions about whether to invest in new machines or prioritizing products based on profit under perturbations. Performance parameters are analyzed under event-based rescheduling in the initial phase. Rescheduling based on input buffer quantity at each machine will also give more insights on system performance under disruption. The integration of real-time optimization with simulation under perturbations with the same or higher complex system has scope for future work.

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