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Research paper

Assessment of Optimal Production Through Assembly Line-Balancing and Product-Mix Flexibility

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Abstract

Timely accomplishment of production targets is a challenging task in low volume–high variety environment. Assessment of the manufacturing flexibility of a production system assists in achieving the desired objectives. In this research, the operational flexibility of a production system is investigated which operates under the low-volume high-variety production scenario. Prospective dimensions of the production flexibility are studied to analyze its interface with the integrated functional units. It was analyzed that with a low-volume operational flexibility (OF) varies rationally despite high job varieties. Line-balancing and queuing techniques are applied to ascertain the optimum productivity. A sensitivity analysis is also performed to evaluate the critical parameters that affect the OF and productivity level. OF index of the production system was estimated by means of the optimized production parameters. A comparative analysis is performed to evaluate the flexibility in conventional and flexible production cells. Analytical and computational results show a close approximation and validate the implemented schemes.

Keywords: *Operational flexibility, Productivity, Production simulation, Line balancing*

1. Introduction

Performance indicators of the manufacturing system can be categorized into tangible and intangible factors [1]. Tangible factors include the production rate, cycle time, machining capacity, and production volume. Intangible factors include the operator flexibility, quality level, and responsiveness. Intangible factors are difficult to determine but they play a crucial role in system stability and performance. System flexibility is also an intangible factor which is difficult to manage while dealing with high-variety low-volume production. OF shows the ability of a system to interchange the sequence of operations required to produce a part [2]. In some cases, flexibility can be taken as a freedom to redirect the production activities to different machines when the proposed machines are overloaded [3]. Flexibility also interacts with the marketing strategy to respond proficiently to change the product mix and introduce the new products [4]. So, the flexibility can be considered as a multi-dimensional approach that integrates the marketing and production operations. Process flexibility assists in reducing the batch sizes and inventory costs [5].
Researchers have meticulously explored the dimensions of the flexibility with analytical and computational analyses. However, limited publications are available which deal with the quantifiable approaches to be implemented in the production units pragmatically [6]. In this research, a novel methodology has been implemented in the discrete part manufacturing system to quantify the system's flexibility under customized production targets. Inadequate manufacturing flexibility causes inefficient product planning, production delays, long time-to-market and significant financial losses [7]. Manufacturing flexibility of a production system depends on three main attributes. The first attribute is the availability of the number of options available at a given time to switch among different processes. Second is the mobility with which the organization moves from one targeted state to another with respect to time and cost. The third attribute of manufacturing flexibility is the uniformity or consistency of performance of the customized orders over a period of time.
Assembly line and balancing techniques assign the equal amount of production at all workstations [8]. In this research, assembly lines were studied in perspective of system's operational flexibility. Hafsa et al. [9] worked on the geometric defects and predicted variation of the behavior of flexible parts and assembly. Kara et al. [10] explained that those companies prosper dramatically which focus on numerical controlled technologies, automatic material handling-loading systems and variety of sophisticated cutting tools. Handiness of these resources ensures the company's capability to switch the pallets, fixtures and related accessories within least possible time [11]. Malasamy et al. [12] determined that knowledge acquisition and its relationship quality significantly contributes in product innovation flexibility. Heuristic optimization techniques have also been explored to determine the optimal layout and productivity of production assembly lines. For example, Seamus et al. [13] applied genetic algorithm for robotic assembly line balancing. Alper et al. [14] presented their study on balancing and sequencing of mixed model U-lines by considering the parallel workstations. They applied Genetic Algorithm for sequencing the activities of mixed-model U-shape assembly under different production scenarios. The other heuristic optimization techniques considered for assembly line balancing include ant colony optimization. Simaria and Vilarinho [15] studied the two-sided assembly lines by ant colony algorithm. Mahesh et. Al [16] worked out that simulation tools assist in determining the overall system's production flexibility.

2. OF: Lowest and Highest Limits

The research work presented here deals with the identification of the system's operational flexibility in a low-volume high-variety manufacturing environment. Kostle and Melhotra [7] model was adopted to measure the operational flexibility of the production system. The highest and lowest limits of OF are determined by calculating the maximum production capacity and the break-even point respectively. Since the production orders are rarely repeated, so the machining facility is established by considering the maximum flexibility with a varied set of operations. The area of interest in this research under the volume-variety scenario is explained in figure 1.

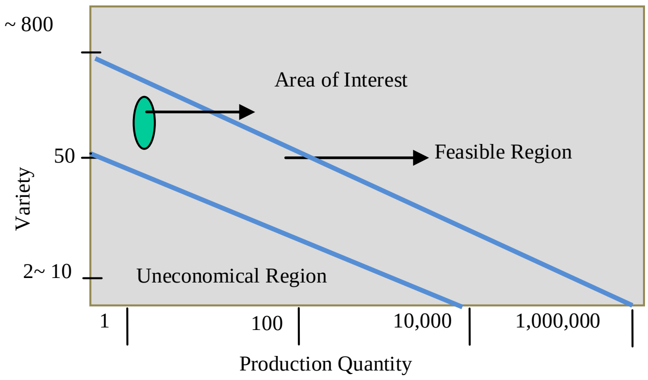

Fig. 1:. Production volume vs variety

The break-even point in a scheduled period is calculated as:

$$Ot_j = \sum_{i=1}^{n} (W_i x T_{ij} x Q_j + TS_{ij}) \quad (1)$$

Where; Q_j = total amount of products that machine j is capable to process, T_{ij} is the processing time of machine j for product i, TS_{ij} is the setup time of machine j to process product i, W_i is the percentage of product i to be fabricated according to product mix. Production time is calculated as:

$$At_j = Tt_j \text{ x } Mt_j \quad (2)$$

Where; At_j is the available time of machine j, Tt_j is the total time when machine j is operational, Mt_j is the maintenance time.
The maximum capacity of each machine is established when the available time of the machine becomes equal to its demand time. The machine with the lowest value (LL) of Q determines the highest limit (HL) of the manufacturing system and acts as a system bottleneck.

$$Ot_j = At_j \quad (3)$$

$$Q_j = \frac{At_j - \sum_{i=1}^{n} TS_{ij}}{\sum_{i=1}^{n} (W_i x T_{ij})} \quad (4)$$

$$Q_{HL} = \min(Q_j) \quad (5)$$

$$OF = Q_{HL} - Q_{LL}$$

Where; Q_{LL} is break-even point (the lowest limit), Ot_j is the product occupation time at machine j.

3. Estimation of Operational Flexibility

A job-shop manufacturing unit is studied to estimate the production manufacturing flexibility and system's performance. Five products were selected to quantify the system flexibility. For each product, the operations sequence, processing time, material handling, and resources were studied including all the delays. Processes of the conventional machining (NC and manual) setup are shown in Table 1.

Table 1: Conventional assembly line

Codes											
Bench Work (Machine A), Turning (Machine B), Milling (Machine C), Hydro-test (Machine D), Inspection (Ip), X1 =Shell 1 (Sections A), X2 = Shell 2 (Sections B), X3= Shell 3 (Sections C) X 4 = Shell 4 (Sections D), X5 = Shell 5 (Sections E)											
Work Element (Processes), Time (Minutes), Sequence											
X1		1	2	3	4	5	6	7	-	-	ABCAD
	Code	A	Ip	B	C	A	D	Ip	-	-	
	Time	20	5	45	20	15	4	5	-	-	
X2		1	2	4	5	6	7	8	-	-	ABCAD
	Code	A	Ip	B	C	A	D	Ip	-	-	
	Time	10	5	15	5	3	2	5	-	-	
X3		1	2	4	5	6	7	8	-	-	ABED
	Code	A	Ip	B	E	Ip	D	Ip	-	-	
	Time	5	5	45		5			-	-	
X4		1	2	3	4	5	6	7	8	9	ABCAEAD
	Code	A	Ip	B	C	A	E	A	D	Ip	
	Time	25	5	120	20	5	5	40	15	5	
X5		1	2	3	4	5	6	7	-	-	ABCAD
	Code	A	Ip	B	C	A	D	Ip	-	-	
	Time	20		45	20	20	4		-	-	

3.1. Conventional Assembly Line

First, the operational flexibility of product X4 was studied to quantify the system's reference flexibility. Shell X4 data is given in Table 2. Where, T_{ek} represents the process time of specified processes. Customers annual demand for the product X4 is 500. The estimated working hours of production unit is 46 weeks per year. In conventional machining setup, only one worker is allocated at each workstation, so the calculations are based on fixed workers. Considering the annual demand, the hourly production rate of system is:

$$R_p = 500/46x5x7 = 0.31 \text{ units/hour}$$

By evaluating the annual machining breakdown time and system performance, the line efficiency (E) of overall production system is assumed 90 percent, therefore, the actual production cycle time is:

$$T_c = 60E/R_p = 60x0.9/0.31 = 174.8 \text{ min.}$$

Material handling and part adjustment time (T_r) is 10 min/cycle. Maximum yearly production time is 96600 min. Based on the estimated production, the lowest production capacity (LL) of systems is 0.9 x 96600 / 250 = 347 parts. Theoretically, the maximum possible production (HL) is 96600/240=402 parts.
Based on the analytical findings, the actual production rate of the system is 347/1610 = 0.215 parts per hour. From the available statistics, the service time of one shell is:

$$Ts = Tc - Tr = 174.8 - 10 = 164.8 \text{ min.}$$

Using the actual and theoretical production capacities, system's overall flexibility was estimated as:

HL– LL = 402-347 = 55 parts.

Table 2: Line balancing (rank position weight)

Work Element	Relative Positional Weight	T_{ek} (min)	Preceded by
1	25+5+120+5+5+ 40+15+5=24	25	-
2	240-25 = 215	5	1
3	210	120	1,2
4	90	20	3
5	70	5	4
6	65	5	5
7	60	40	5,6
8	20	15	5,7
9	5	5	-

3.2. Assembly Line Balancing

Table 3: Advance machining facility data

Production data: CNC machining setup							
X 1	Process	1	2	3	4		A-B-D
	Code	A	B	C	Ip		
	Time	15	15	5	5		
X 2	Process	1	2	3	4		A-B-C-A-D
	Code	A	B	C	Ip		
	Time	10	8	2	5		
X 3	Process	1	2	3	4		A-B-E-D
	Code	A	D	Ip	B		
	Time	20	10	5	35		
X 4	Process	1	2	3	4	5	A-B-C-A-E-A-D
	Code	A	B	D	C	Ip	
	Time	65	10	5	40	5	
X 5	Process	1	2	3	4		A-B-C-A-D
	Code	A	B	C	Ip		
	Time	25	15	5	5		

An assembly line balancing technique is applied to analyze the potential improvement in the system productivity and to determine the operational flexibility limit. Data of the selected products in a flexible manufacturing facility is given in Table 3. After a comprehensive analysis, the bottleneck station was specified to be workstation 2. In this case, the improved production efficiency is:

$E_b = T_{wc}$ / Workstation service time = 240 / 3 x150 = 0.534

Cycle time = $T_c = T_s+T_r$ = 150+10 =160 minutes

R_c = Production line cycle time = 60/Tc= 60/160=0.375 cycles/hr

$R_p = R_c$ x 0.9 =0.375 x 0.9 = 0.3375 units/hr

The improved production rate with a balanced line approach is, 0.3375-0.215= 0.122 units/hr

In a balanced production line, total parts produced are:

0.3375 x 1610 = 543 pars / year

In the flexible manufacturing system, bottleneck was observed to be work station 1. So the estimated production was calculated as:

Total time: T_{wc} =125 min, $T_c = 115+T_r = 125$, $R_c = 60/T_c = 0.48$,

$R_p = R_c$ x 0.9 = 0.432

Increased production rate = 0.432-0.215 = 0.217 units/hr

Parts produced in flexible system =0.432 x 1610 =695 pars / year

Operational flexibility = 695 – 347 = 348 parts

4. Computational Analysis

Table 4: OF – Conventional and flexible Systems

	Analytical findings			Simulation results		
Mode of production	LL	HL	OF	LL	HL	OF
Conventional assembly line	347	402	55	347	390	43
Conventional production line	347	543	196	347	565	217
Flexible assembly line	347	695	348	347	702	355

A comparison of the parts produced in flexible and conventional systems is given in Table 5. Arena simulation software was used to simulate the system performance and to evaluate the analytical results. Additionally, Arena was used to determine the optimal product-mix strategy. The configuration layout of model 1 is shown in figure 2. Simulation results of model 1 are shown in Table 5. Simulation results show a close approximation with analytical outcomes. The discrete change variables showed a total percentage of time taken by particular workstations. By using the simulation results, the operational flexibility of production system is, HL – LL = 390-347 = 43 parts.

By means of line balancing technique, the operational flexibility of shell X4 was verified with a modified simulation model. Simulation results of model 2 show that in the balanced production line operational flexibility increases significantly. Analytically, only 196 parts were estimated, which means that simulation results vary by 10 percent. For shell X4, five workstations are modelled which represents the actual production sequence. The computational analysis shows a close approximation with analytical findings. Based on the simulation results, the system OF is HL–LL=702-347=355 parts.

5. Results and Discussion

Comparison of the simulated operational flexibility of different production models is presented in Table 5. The same is also explained in figure 3. A sensitivity analysis of is performed by changing the manufacturing time and input variables. Results are presented in Table 6. It is observed that if the total work content time of a single shell is kept constant then the value of total number of parts produced remains constant over a number of simulation replications. For example, for model 1, simulation results remain same over with certain number of replication and closely match with the total number of parts estimated analytically. This value is similar to analytical findings in conventional machining setup. It is also observed that the output depends linearly on the arrival rate. A decrease in the inter arrival time increases the production output. With the help of analytical results, a limiting factor was established to represent the maximum system capacity with a fixed line efficiency.

Table 5: Comparison of operational flexibility

Product Variety	Conventional System	Flexible System
X 1	114	45
X 2	45	25
X 3	100	70
X 4	240	125
X 5	119	50

Table 6: Sensitivity analysis – Production and arrival rate

Model 1		Model 2		Model 3	
Time (hour)	Parts/year	Time (hour)	Parts/year	Time (hour)	Parts/year
59.5	1485	123	643	60	1485
60	1485	130	643	125	772
80	1206	150	643	150	643
120	804	170	567	200	483
160	603	190	508	280	345
200	483	210	459	300	322
240	402	240	402	320	302

6. Conclusion

In this research, a methodology is developed to establish the production flexibility in terms of maximum system performance. Performance of a production system can be analyzed under different product variety-volume scenarios. Similarly, the maximum manufacturing flexibility may be established with an optimal production capacity under the defined bottlenecks. Especially, in low-volume high-variety production environment, an optimized product-mix can be defined by establishing a limiting factor to avoid the parts clustering. Lowest production limit can also be upgraded by identifying the operational flexibility and production line-efficiency. The implemented scheme can be applied to a batch-production system to enhance the productivity and system performance.

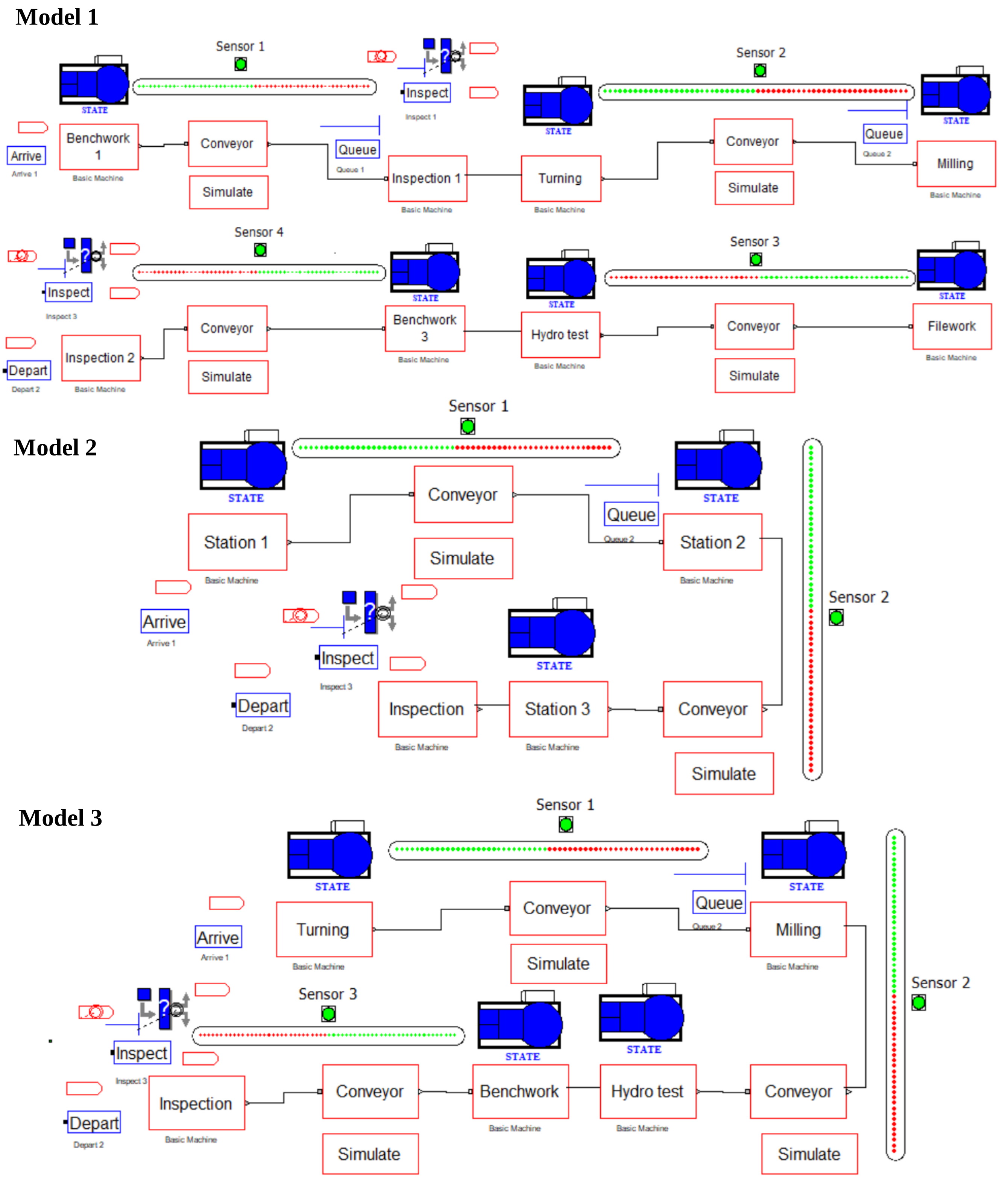

Fig. 2. Configuration layout - Production Simulation Models

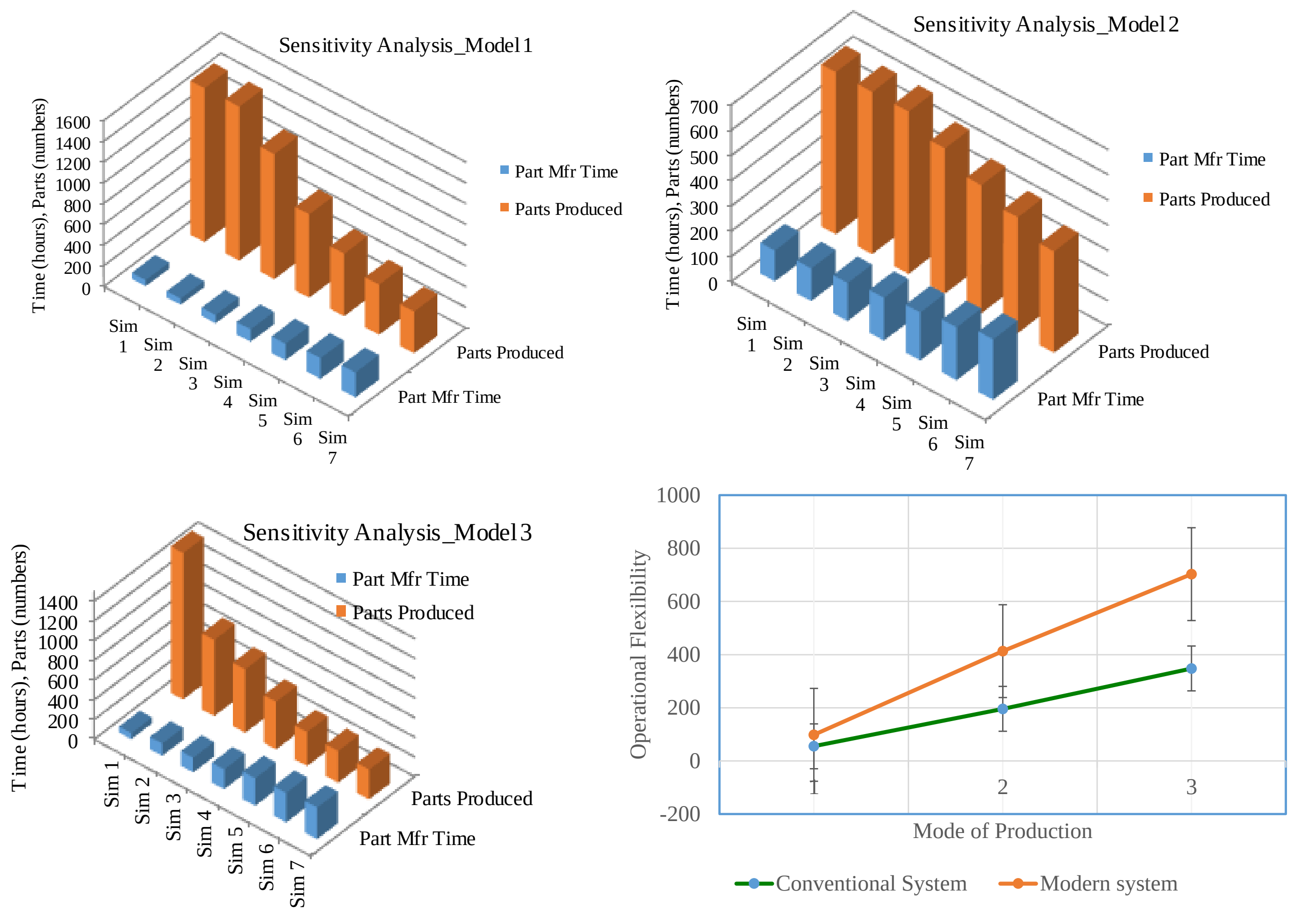

Fig 3:. Sensitivity analysis – parts arrival rate

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