Cost-Benefit Analysis of Flexible Manufacturing Systems

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Abstract

FMS offers flexibility in dealing with varied part and product designs, and allows variation in parts' processing sequences and production volume changes. Its successful implementation results in improvement of capital utilization, higher profit margins, and increased competitiveness. Today, FMS design is a complex process where various layouts, material handling system and processing plans exist while part inter-arrival and processing times are stochastic. This paper presents a case study to investigate the effect of different input factors, including layout, MHS configuration (number, speed and type) on FMS performance measured by total production cost, total flow time and throughput. The investigation includes the interaction between those input factors, and quantifies the effects of these interactions on FMS performance. Furthermore, cost-benefit analysis between various layout and MHS configurations is conducted to determine production volumes' break-even points for layout and MHS selection.

Keywords
Flexible Manufacturing Systems, Experimental Design, Cost-benefit Analysis

1. Introduction

A Flexible Manufacturing System (FMS) addresses dynamic production needs and operations. It uses programmable machines integrated with an automated Material Handling System (MHS) under a central controller to produce a variety of parts at non-uniform production rates, batch sizes and quantities (Leondes, 2003, Shivanand et al., 2006). It offers flexibility in dealing with mixed part types and varied product designs, allowing variation in parts' processing, assembly sequences, and production volumes. Successful FMS implementation results in decreased production cost, lead time, inventory, tooling, direct labor content, floor space, Work-in-Process (WIP) and assembly (Saygin et al., 2001). It can result in improvement of capital utilization, better quality, higher profit margins, and increased competitiveness (Chen and Adam, 1991, Seidmann, 1993, Su, 2007, Singholi et al., 2010).

Today, FMS presents various difficulties encountered through the design, planning, scheduling, and control of these systems. Consider the following: A manufacturing facility would like to install m-machine centers that perform t-variety of tasks for n-part types and uses v-Automated Guided Vehicles (AGVs), etc. The decision-making situation is further complicated where various layout types and MHS devices exist and part inter-arrival and processing times are stochastic. The manufacturing managers like to evaluate their FMS performance prior to making costly investment decisions. In order to facilitate the decision-making process for managers, and realize flexibility and cost saving benefits associated with FMS, there is a need to conduct research and develop tools to analyze and design complex manufacturing systems (National Research Council, 1988).

This paper investigates the effects of several factors such as layout and MHS configuration (which includes number of units, speed and type), under stochastic parts inter-arrival and processing time, on total production cost, total flow time and throughput. A simulation-based study emphasizes the interactions between those input factors and determines production volumes that result in cost break-even points for layout and MHS selection.

2. Literature Survey

Several authors had studied design, planning, scheduling, and control of FMS and proposed various techniques to model and analyze FMS performance. They embraced various problems such as selection of best dispatching, scheduling, routing and control rules, determination of optimal number of machines, optimal number of AGVs and/or buffers/pallets, and optimization of a specific product machining parameter (such as full load speed of sheet metal piler) (Basnet and Mize, 1994, Chan et al., 2002). Diverse factors such as AGVs availability, variable machining time, system layout, routing and sequencing flexibility and part mix were considered (Solot and Vliet, 1994, Chan and Chan, 2004). Performance criteria such as make-span (time to complete all jobs), tardiness (the difference between completion times and due dates), total processing time, flow time, production rate, cost and machine utilization were assessed (Azimi et al., 2010, Joseph and Sridharan, 2011, Kumar and Sridharan, 2011, Singholi et al., 2010). In addition, various approaches and models were used in FMS research such as mathematical programming (Abou Gamila et al., 2000), multi-criteria decision making (Karsak, 2000), dynamic programming (Ecker and Gupta, 2005), goal programming (Chan and Swarnkar, 2006), petri-net (Hamid, 2010), linear and non-linear programming (Chan and Chan, 2004) and investment model (Bruce and Albert, 1999).

Today, FMS is complex due to variation in layout, MHS configuration, and stochastic parts inter-arrival and processing times, which makes FMS problems multidimensional in nature (Saygin et al., 2001). It might be difficult to use analytical approaches to model a complex manufacturing environments such FMS with their entire operating and physical characteristics. Analytical modeling will be further complicated to use when dynamic operating environments and control time aspect are considered (Chan et al., 2007). Furthermore, the analytical modeling approaches are usually based on simplifying assumptions for the system under study and specific to individual manufacturing enterprises and processes (Chan et al., 2002). These assumptions may not provide an actual image of FMS performance and may not be representative of real-world cases (Chan et al., 2007).

On the other hand, simulation-based approaches have been used for modeling and analyzing complex manufacturing systems, since they can model the variables which are mathematically complicated, and represent more realistic environments (Singholi et al., 2010). It also can deal with stochastic environments, for which analytical models such as mathematical programming have been inferior without major simplifications (Chan and Chan, 2004). McLean and Kibira (2002) concluded that simulation could be the best decision-making aid during design, analyze and improvement of manufacturing systems.

Several authors used simulation to model and analyze FMS performance. Yifei et al. (2010) discussed AGV fleet size determination in FMS using estimation and simulation. They estimated the AGV fleet size mathematically and applied the results in a simulation model of AGVs for further evaluation. Studying scheduling problems, Shafiq et al. (2010) proposed a framework for studying the effect of scheduling, system configuration, buffer capacity, routing flexibility (manufacturing flexibility), number of pallets, volume of parts, dispatching and sequencing rules (scheduling rules) on FMS performance (i.e., make-span time, cost, machine utilization and queue waiting time). They concluded that the make-span and queue waiting time decrease while machine utilization and production cost increase with the increase in routing flexibility level.

Discussing performance analysis problems, Singholi et al. (2010) conducted a real FMS case study to analyze its existing performance such as maximum production rate, make-span and overall utilization, determined by a quantitative modeling, and prepared an improvement plan to be compared with the existing using simulation modeling. The modification includes adding resources (i.e., sizing the system) and implementing new layout. The results showed that the proposed FMS has increased of the number of servers, maximum production rate and overall utilization of resources. Meanwhile, Abou-Ali and Shouman (2004) discussed a study of the effect of 12 dynamic and static dispatching strategies on dynamically planned and unplanned FMS consisting of eight machines, storage buffer areas, receiving area, and three robots and pallets. The authors showed that an overall improvement could be achieved for dynamic dispatching than that rendered by static dispatching.

Taken together, past simulation-based FMS research emphasized specific problems such as determination of MHS size; layout design; production parameters determination; part and resource dispatching/scheduling and allocation; and selection of real-time control strategy. Different factors were considered such as scheduling, control, and loading rules; product mix, stochastic arrival and waiting time; tool breakdown and maintenance; machine number & availability; MHS availability; operation, arrival and setup time. Diverse performance criteria were also assessed, such as resource utilization, throughput, make-span, flow time, waiting time, queue length, and production cost.

2.1 Problem Definition

There is a need to investigate the effects of input factors, including various layout types and MHS configuration (type, number and speed), under stochastic parts arrival and processing time) on FMS system performance measured by total production cost, total flow time and throughput. This investigation uses simulation and experimental design to study these effects, and applies cost-benefit analysis between various layout and MHS configurations to determine production volumes' break-even points for layout and MHS selection.

3. Case Study

This research uses a hypothetical case study for designing a company that produces 10 part types. These parts, in the to-be designed production line, undergo a series of processes, including: (G1) Turning, (G2) welding, (G3) drilling, (G4) milling, and (G5) grinding, with different machining sequences. Due to dynamic service needs, the company plans to process the parts using a job shop FMS.

At the shop floor, parts arrive at the arrival station with stochastic inter-arrival times. In this station, parts are loaded on a MHS device, with loading time of 0.25, and then routed to workstations based on their processing plans, as indicated in Table 1. For example, the first part will undergo process sequence of G1-G4-G5-G3. Parts inter-arrival time is assumed to be exponentially distributed with a mean of 10 minutes, while the processing time, which includes machine setup and tool changing time, is assumed to be normally distributed with mean and standard deviation as indicated by Table 1 in the rows of duration. Once parts arrive at working station, they are unloaded into queues in front of machine groups with unloading time of 0.25, and then processed on a first-come-first-served basis by an available machine in the group. Each operation has an assumed stochastic operational time. After finishing all sequential operations, a part is ready for shipping.

Table 1: *Processing Plan for Different Part Types*

Part Type	Process Plan				
	Attributes	**Step 1**	**Step 2**	**Step 3**	**Step 4**
1	Sequence	G1	G4	G5	G3
	Duration / Cost	NORM(10,2) / 12	NORM(25,3) / 18	NORM(25,1) / 4	NORM(30,1) / 24
2	Sequence	G4	G3	-	-
	Duration / Cost	NORM(30,2) / 22	NORM(25,1) / 21	-	-
3	Sequence	G2	G3	G5	G4
	Duration / Cost	NORM(30,1) / 20	NORM(22,1) / 16	NORM(27,2) / 5	NORM(26,3) / 19
4	Sequence	G1	G4	G3	G2
	Duration / Cost	NORM(8,2) / 10	NORM(22,3) / 15	NORM(24,3) / 16	NORM(35,3) / 22
5	Sequence	G3	G2	-	-
	Duration / Cost	NORM(22,2) / 15	NORM(27,2) / 20	-	-
6	Sequence	G5	G4	G1	G3
	Duration / Cost	NORM(25,1) / 4	NORM(25,3) / 18	NORM(10,2) / 12	NORM(30,1) / 24
7	Sequence	G1	G5	-	-
	Duration / Cost	NORM(10,2) / 12	NORM(25,1) / 4	-	-
8	Sequence	G3	G4	G5	-
	Duration / Cost	NORM(22,2) / 18	NORM(33,3) / 25	NORM(19,2) / 7	-
9	Sequence	G4	G3	G2	-
	Duration / Cost	NORM(26,3) / 19	NORM(27,3) / 22	NORM(24,3) / 18	-
10	Sequence	G3	G4	G1	-
	Duration / Cost	NORM(18,1) / 20	NORM(15,1) / 15	NORM(12,1) / 9	-

4. Experimental Design

The different factor combinations are obtained using experimental design. Factor combinations resulting from the experimental design are used to develop different simulation models for the case study.

4.1. Performance Measures

This research investigates effects of several factors on FMS performance as measured by total production cost, total flow time, and throughput.

4.2. Factors

There are two main factors considered in this experiment: layout and MHS configuration. Table 2 illustrates the variations among those factors.

Table 2: *Variations of Factors*

Layout	MHS Configuration			
	Device	Number (unit)	Speed (feet/min)	Type
Loop Layout	Cart	1 or 3 or 5	5 or 10	-
U-Layout	AGV	1 or 3 or 5	5 or 10	-
Line Layout	Conveyor	1	5 or 10	Accumulating or Non-accumulating

4.3. Experimental Design Table

A full factorial experimental design is applied to obtain all factor combinations. Table 3 illustrates the various factor combinations resulting from the experimental design. Total number of models in the experiment is 48 models.

Table 3: *Experimental Design Table*

Cart Models

#	Layout	Configuration	
		Number	Speed
1	U	1	5
2	U	3	5
3	U	5	5
4	U	1	10
5	U	3	10
6	U	5	10
7	Line	1	5
8	Line	3	5
9	Line	5	5
10	Line	1	10
11	Line	3	10
12	Line	5	10
13	Loop	1	5
14	Loop	3	5
15	Loop	5	5
16	Loop	1	10
17	Loop	3	10
18	Loop	5	10

AGV Models

#	Layout	Configuration	
		Number	Speed
19	U	1	5
20	U	3	5
21	U	5	5
22	U	1	10
23	U	3	10
24	U	5	10
25	Line	1	5
26	Line	3	5
27	Line	5	5
28	Line	1	10
29	Line	3	10
30	Line	5	10
31	Loop	1	5
32	Loop	3	5
33	Loop	5	5
34	Loop	1	10
35	Loop	3	10
36	Loop	5	10

Conveyor Models

#	Layout	Configuration	
		Type	Speed
37	U	Acc	5
38	U	Acc	10
39	U	Non-Acc	5
40	U	Non-Acc	10
41	Line	Acc	5
42	Line	Acc	10
43	Line	Non-Acc	5
44	Line	Non-Acc	10
45	Loop	Acc	5
46	Loop	Acc	10
47	Loop	Non-Acc	5
48	Loop	Non-Acc	10

5. Method

5.1. Simulation

Simulation models of the to-be designed FMS are developed using Arena Enterprise Suite Academic version 13.90. All models are built by incorporating all basic elements of the FMS, such as machine groups, machining and non-machining (arrival and exit) stations, and so on. Each model incorporates different type of layout and MHS configuration as given by the experimental design (see Table 3), combined with the processing plans of each part. Animation is used in order to enable continuous visual verification of the simulation model. Figure 1 depicts the overall simulation flowchart and animation.

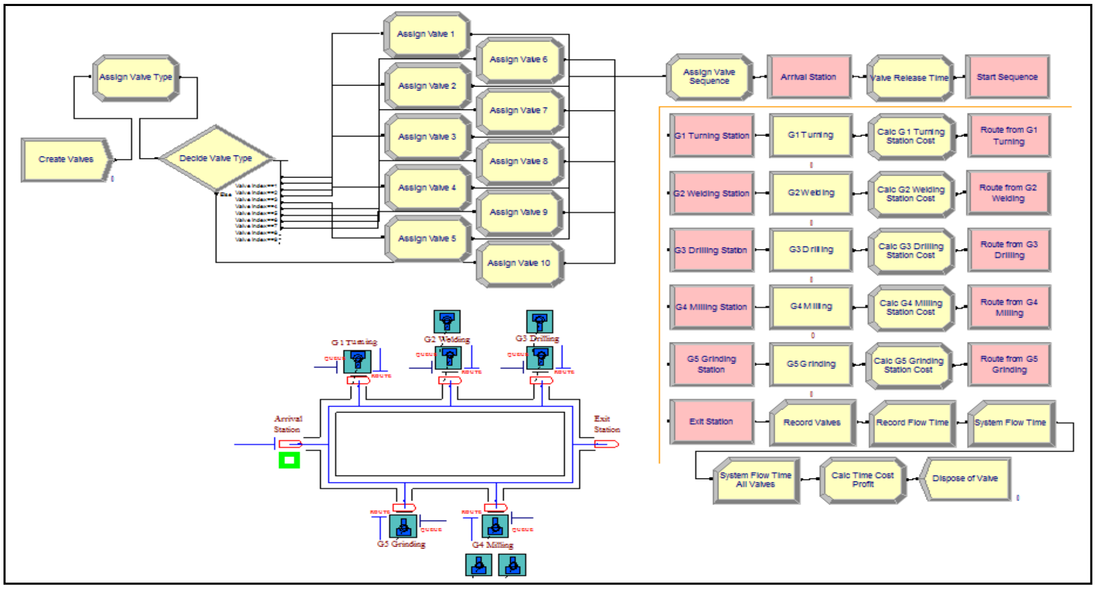

Figure 1: *Arena Flowchart Modules and Animation Model*

Once simulation models are developed, verification is applied to those models. The verification is done by visually determining that each part type undergoes the desired operation sequence using Arena animation, and comparing processing time and transfer time for each part type, as well as the total cost from simulation results to analytical calculations. The results show that those simulation models behave as the authors intend. Meanwhile, since the simulation is for hypothetical case (not an existing system), validation is inapplicable for these models.

Furthermore, simulation of FMS is a non-terminating simulation, since the simulation runs continuously over time. Any job which is not fully processed by current shift will be WIP to be finished during the next shift or day, until processing is complete. Hence, this FMS simulation utilizes *steady-state parameters* consisting of *warm-up period*, *number of replications* and *run length*. An initial run is performed to help the determination of these parameters. The result of this initial run suggests executing the simulation using warm-up period of 4 hours, number of replication of 30 and 24 hours run length. Simulation is then run for the 48 models.

5.2. Cost-benefit Analysis

Cost-benefit analysis applies a systematic procedure for identifying, calculating and comparing benefits and costs of various policy options. It provides a basis of comparing the total expected cost of each option against the total expected benefits, to see whether the benefits outweigh the costs, and by how much (Devorshak, 2012). It is conducted to determine production volumes' BEP and compare several options of layout and MHS selection.

6. Results

6.1. Factorial Design Analysis

The effects of factors and their interaction on FMS performance, investigated using factorial design are summarized in Table 4. A check mark (√) represents a statistically significant effect of corresponding factor or interaction (i.e., P-value <0.05). Number is used for Cart and AGV models, and Type is used for Conveyor models.

Table 4: *Summary of Factor Effects*

Factor / Interaction	Cart Models			AGV Models			Conveyor Models		
	Cost	Time	Throughput	Cost	Time	Throughput	Cost	Time	Throughput
Layout				√	√	√	√	√	
Speed	√	√	√	√	√	√	√	√	√
Number (Type)	√	√	√	√	√	√	√	√	√
Layout*Speed								√	
Layout*Number			√	√	√	√		√	
Speed*Number	√	√	√	√	√	√		√	√

6.2. Cost-benefit Analysis

Cost-benefit analysis is performed to find production volumes that result in break-even points for layout and MHS selection. Figures 2, 3, and 4 provide the results of production volumes' break-even points for layout and Figures 5, 6, and 7 for MHS. As an example, for cart models, layout types are (U, line, and loop), and the MHS configuration used for comparison is 1 cart with speed of 10. After performing cost-benefit analysis, the intersections between U, Line, and Loop layouts are shown in Figure 2.

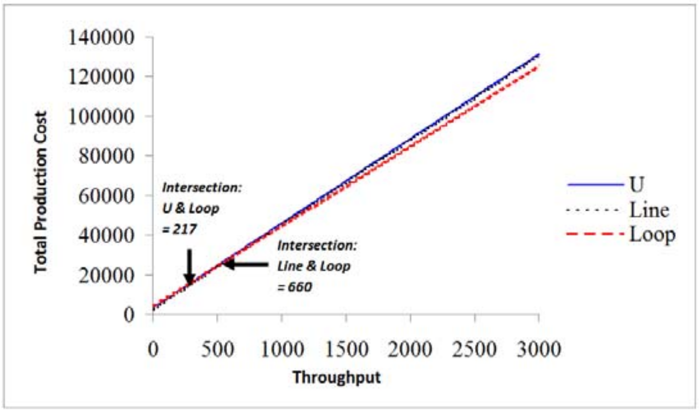

Figure 2: *Layout breakeven analysis for Cart MHS (1 Cart, speed =10)*

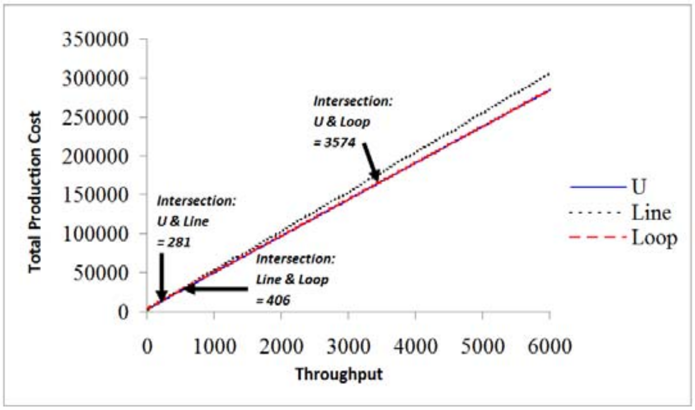

Figure 3: *Layout breakeven analysis for AGV MHS (1 AGV, speed =10)*

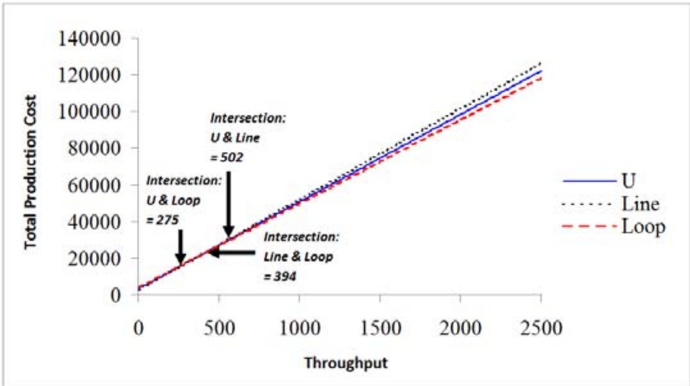

Figure 4: *Layout breakeven analysis for Conveyor MHS (Non-accumulating, speed =10)*

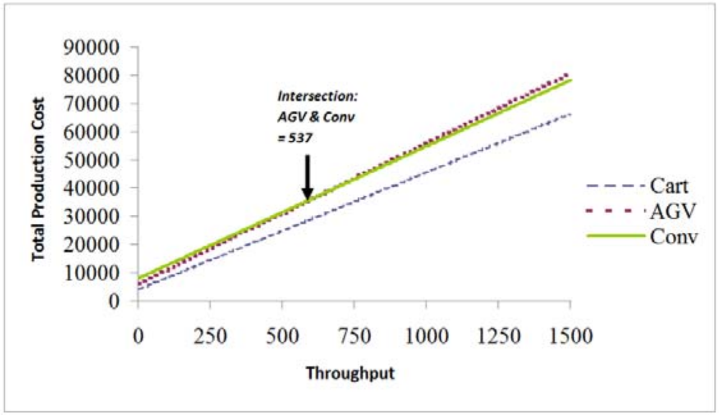

Figure 5: *MHS breakeven analysis for U- layout (5 carts and AGVs, accumulating conveyor, speed =10)*

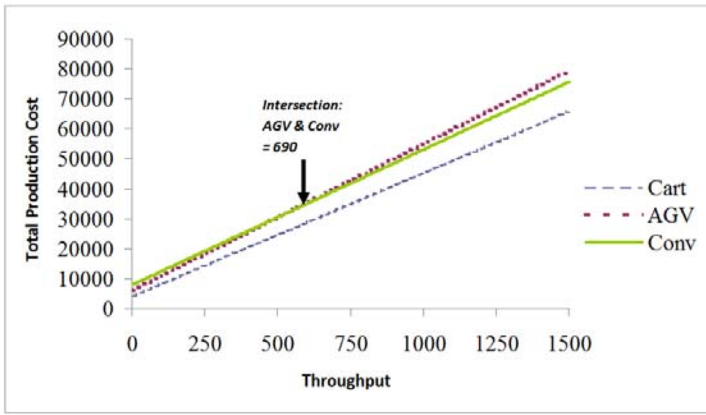

Figure 6: *MHS breakeven analysis for Line layout (5 carts and AGVs, accumulating conveyor, speed =10)*

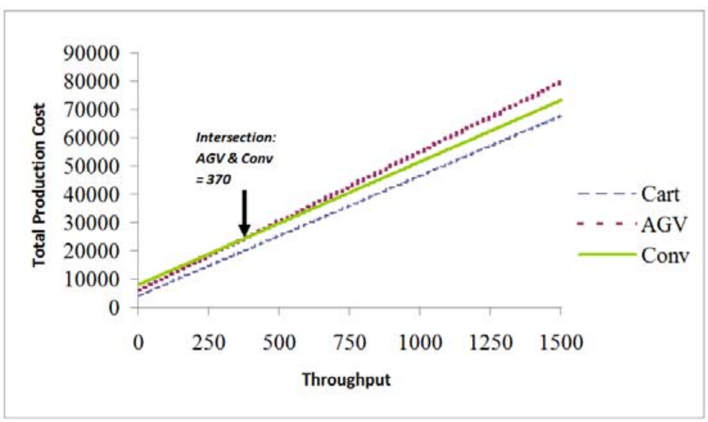

Figure 7: *MHS breakeven analysis for Loop layout (5 carts and AGVs, accumulating conveyor, speed =10)*

7. Discussion and Conclusions

This study extends current state-of-the-art in simulation-based FMS design research. It applies experimental design, simulation and cost-benefit analysis to model and analyze such complex manufacturing systems, which are mathematically challenging. Simulation allows for including stochastic components that are inherent in real world systems. The experimental design and simulation results show that layout and MHS configuration affect manufacturing system performance. This is in agreement with past research, where layout affects cost (Rao and Gu, 1997), flow time (Prakash and Chen, 1993) and throughput (Singholi et al., 2010), whereas number of MHS units and their speed affect throughput (Rao and Gu, 1997, Shang, 1995, Hwang and Kim, 1998).

Some potentially useful contributions of this research to FMS design include:

- Number of carts (or AGVs) has a significant effect on total production cost, total flow time and throughput
- Speed of MHS has a significant effect on total production cost, total flow time and throughput
- Type of conveyor has a significant effect on total production cost, total flow time and throughput

The results from cost-benefit analysis indicate the following:

1) If a cart-based MHS is used, the cost break even points are the intersection of U and Loop (217), Line and Loop (600), vertical lines from these points show the levels of production necessary to cover the total production cost
2) If an AGV-based MHS is used, the cost break even points are the intersection of U and Line (281), Line and Loop (406), U and Loop (3574) vertical lines from these points show the levels of production necessary to cover the total production cost
3) If a conveyor-based MHS is used, the cost break even points are the intersection of U and Loop (275), Line and Loop (394), U and Line (502), vertical lines from these points show the levels of production necessary to cover the total production cost
4) If U layout is used, the cost break even points is the intersection of AGV and conveyor (537), a vertical line from this point shows the level of production necessary to cover the total production cost
5) If Line layout is used, the cost break even points is the intersection of AGV and conveyor (690), a vertical line from this point shows the level of production necessary to cover the total production cost
6) If Loop layout is used, cost break even points is the intersection of AGV and conveyor (370), a vertical line from this point shows the level of production necessary to cover the total production cost

The key conclusions from this research include:

1) FMS performance is influenced by the choice of MHS and layout. Thus, when designing an FMS, decisions should be made based on production volumes' break-even points for layout and MHS selection
2) Designing complex manufacturing systems involves the consideration of production volumes' break-even points to cover the total cost for different design configurations. and different performance measures

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