ECONOMIES OF SCALE AND SCOPE IN MANUFACTURING SYSTEMS - A BENCHMARKING APPROACH

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ABSTRACT
The main purpose of this study is to benchmark the economics of scale and scope (EoSS) for three different manufacturing systems layouts namely; functional, cellular and fractal layouts. The effect of setup reduction factor (SRF) on the EoSS of the mentioned layouts is also included in this study. Firstly, simulation modelling is employed to model and generate the necessary performance measures of these proposed layouts and then, EoSS levels are generated using mathematical programming. This study revealed that, fractal layout (FrL) showed the highest level of EoSS followed by cellular layout (CL) and then functional layout (FL). Additionally the findings of this study are in line with previous studies about the effect of SRF on the CL and the relative level of EoSS in the FL and CL. While majority of previous research focused on the comparison of functional and cellular layouts, it is clear that evaluating the EoSS attracted little attention in the past; therefore, the originality of this research work is threefold. Firstly, the evaluation of EoSS, secondly, the consideration of the FrL in the comparison as one of the 21st century manufacturing systems and lastly the development of the parts routing for the FrL is intelligently defined in the simulation model.

Keywords: Economies of scale and scope, Functional, Cellular, Fractal, Manufacturing layout

1. INTRODUCTION

It has been a while that manufacturing systems face complexity and decrease in productivity as a result of increase in plant size , machine production rates, part complexity and most importantly volume and mix of parts. In order to overcome such mentioned issues the layout of manufacturing systems has been under great attention. Since the middle of the past century this concern has led to emergence of the cellular layout (CL) and apparition of its expansion, a fractal layout (FrL) as a substitute of the traditional functional layout (FL) (Askin, et al., 1999). In the FL, same types of machines are physically groups into machine centres. This indicates that the number of work centres is equal to the number of machine types. Parts can be processed by any machine in a machine centre and there might be as many queues as the number of machine centres in this type of layout. In contrast with FL, machines of CL are grouped to serve families of products. Moreover machines within each cell are dedicated to process certain parts, and each cell of CL may consist of different machine types. Then queues may be made in front of every machine in CL (Co & Araar, 1988). Most importantly, in the factory with fractal design, the layout is divided into smaller cells or fractals which are very similar in that they are autonomous and products are well distributed between them. This similarity enables each fractal to produce all type of products. Also the moving distances between operations within each fractal are minimised. Contrary to CL in which cells were specialised to the particular product types, in the FrL each fractal is able to produce wide range of parts (Askin, et al., 1999).

Firms in any industry may achieve two types of production economies namely; economies of scale and economies of scope. While the first is associated with the firm size the latter relates to the joint production of two or more firms (Clark, 1988). Measures of EoSS can be obtained through the study of relationship between inputs and outputs by means of best practice production frontier. Therefore, the data envelopment analysis (DEA) which uses mathematical programing method is used to evaluate the relative efficiency of different firms to the best frontier (Bogetoft, 2012).

The comparison of different manufacturing systems has been the subject of numerous researches recently. While these studies have conflict in their results, they were comprehensively categorised and reviewed by some researchers such as; (Chtourou, et al., 2008), (Agarwal & Sarkis, 1998) and (Negahban & Smith, 2014). Study of these revision articles showed that the comparison studies mainly revolved around functional and cellular layouts. Moreover, while researchers rigorously have considered the most important performance factors of these two layouts, the economical evaluation is still the missing element of these studies. The author's research also showed that the literature lacks any comparison study consisting new generation layouts, like FrL.

The main purpose of this research is to compare the relative level of EoSS between three manufacturing layouts including functional, cellular and fractal. This goal is sought to accomplish by two methods of simulation modelling and then efficiency analysis by mathematical programming. The reminder of this paper is organised as follows; the next section, two, consists of the methods, based on which, this study was constructed. Section three exclusively presents the configuration and layout features of the modelled manufacturing layouts in this study. In section four the important and complicated components of simulation models are explained. Then followed by the models verification and validation using different techniques. Experimental design is also developed and lastly the results of the simulation study are presented and analysed. The paper ends with the conclusion section.

2. METHODOLOGY

2.1. Simulation Modelling

In order to generate the necessary values of performance measures, simulation is utilised in this research work. Computer simulation is one of the most popular research methodologies implemented in the operation management (Shafer & Smunt, 2004). Due to competition to improve productivity and quality, simulation is used to study the real behaviours of manufacturing systems in order to identify underlying issues. Because of high cost of complex systems, equipment and facilities, simulation model of such systems can reduce the cost of failure. Simulation analysis of production plan and control, product chain management and logistics, and production scheduling can represent real scenarios to pinpoint system issues and improve key performance indicators of systems (Shahin & Poormostafa, 2011).

Kelton, et al. (2015) observed the simulation from practical point of view and explained that; simulation is the process of designing and creating the computerised model of the real or suggested system, in order to analyse and evaluate the conditioned behaviour of that real system by numerical experiment. Also these authors claimed that the advantage of the simulation model over other modelling methods is that; simulation can produce the desirable model and can even make a more complex model than other modelling methods which may need simplifying assumptions to allow analysis.

2.2. Efficiency Analysis:

Most of economic measure of efficiency can be defined as ratios of measure of total productivity factor (*TPF*). *TPF* of multi-output multi-input firm is the ratio of an aggregate output to an aggregate input. If $x_{it} = (x_{1it}, \dots, x_{Kit})'$ and $q_{it} = (q_{1it}, \dots, q_{Jit})'$ denote the input and output quantity vectors of firm i in period t, then the TPF of the firm i is defined by (O'Donnell, 2011) and can be calculated using equation (1):

$$TPF \equiv {Q_{it}}/{X_{it}} \quad (1)$$

Where:

- $Q_{it} = Q(q_{it})$ is an aggregate output,
- $X_{it} = X(x_{it})$ is an aggregate input.
-

Then measures of residual scale and mix efficiency which are the measures of productivity related to economies of scale and scope, can be calculated by the following equations (O'Donnell, 2011);

$$RISE_{it} = \frac{Q_{it}/\hat{X}_{it}}{TFP_t^*} \leq 1 \quad (2)$$

$$ROSE_{it} = \frac{\hat{Q}_{it}/X_{it}}{TFP_t^*} \leq 1 \quad (3)$$

$$RME_{it} = \frac{\tilde{Q}_{it}/\tilde{X}_{it}}{TFP_t^*} \leq 1 \quad (4)$$

The following notation describes equations 2 to 4.

- $ROSE_{it}$: residual output-oriented scale efficiency of firm i in period t,
- $RISE_{it}$: residual input-oriented scale efficiency of firm i in period t,
- RME_{it}: residual mix efficiency of firm i in period t,
- TPF^*: maximum *TPF* that is possible using the technology available in period *t*,
- $\hat{Q}_{it}$: maximum aggregate output possible when using x_{it} to produce any output vector,
- $\tilde{Q}_{it}$: aggregate output achieved when *TPF* is maximised subject to the constraint that the output and input vectors are scalar multiplies of q_{it},
- $\tilde{X}_{it}$: aggregate input achieved when *TPF* is maximised subject to the constraint that input vectors are scalar multiplies of x_{it} ,

3. SYSTEMS DESCRIPTION

The research showed that the only case study for which functional and cellular layouts are designed is the one that represented by (Co & Araar, 1988). This case study was originally a job shop which consists of 10 different machine types. Moreover, the system is fed with 15 different product types that totally require 95 operations. Table 1 shows the routings, processing times and the distribution of the different product types. Overall this job shop system consists of 67 machines with different capacity. Table 2 displays the number of machines for each machine type as well as capacity of each machine. For example, for machine type 1, there are four copies with number of hours available per week 20, 15, 10 and 30 in turn.

Table 1: Job routing and processing times (minutes) (Co & Araar, 1988)

	Machine type										
Jobs	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Job Distribution**
1	10	-	15	7	-	-	20	17	-	8	0.10
2	-	15	10	-	10	5	-	15	15	-	0.15
3	-	11	13	20	15	-	-	-	12	10	0.07
4	9	10	20	-	-	-	17	9	-	8	0.06
5	15	-	-	15	9	7	12	7	9	-	0.05
6	8	6	-	10	7	13	8	-	-	-	0.06
7	-	-	-	13	12	7	19	-	13	14	0.08
8	12	-	11	-	18	11	-	13	-	10	0.07
9	17	8	6	9	20	-	-	-	12	13	0.06
10	-	7	-	5	-	6	-	12	-	18	0.07
11	12	-	13	-	8	-	11	-	9	-	0.05
12	7	6	5	-	-	-	11	12	13	17	0.04
13	-	15	20	13	-	17	-	12	-	5	0.04
14	18	12	-	7	9	8	-	20	-	-	0.04
15	20	13	5	7	12	13	20	13	7	5	0.06
											1.00

Table 2: Machines' capacity per week (Co & Araar, 1988)

	Units (Number of copies of each machine)									
Machine type	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	20	15	10	30						
2	16	29	15	25	30	20	28			
3	17	15	40	30	10					
4	18	19	17	28						
5	15	20	30	20	20	20	30			
6	18	20	15	15	10	15				
7	10	20	20	10	15	20	15	15	15	10
8	20	20	15	15	10	10	10			
9	18	17	20	30	40	30	20	17		
10	20	10	10	10	30	30	30	15	15	

Presentation of parts' sequences is graphically illustrated by (Co & Araar, 1988). However, table, 3 was adapted from (Montreuil, 1999) who inferred part's sequences from the original paper.

However, fractal layout configuration used in this study is adapted from (Venkatadri, et al., 1997). This fractal layout is generated based on the same data in the case study of (Co & Araar, 1988). In order to design the fractal layout, (Venkatadri, et al., 1997) implemented an integrated design approach.

Table 3: Processing sequences (Montreuil, 1999)

Product types	Processing sequences
1	1, 4, 7, 3, 10, 8
2	3, 9, 2, 8, 5, 6
3	2, 3, 4, 5, 9, 10
4	1, 7, 8, 10, 2, 3
5	5, 6, 8, 1, 4, 7, 9
6	5, 2, 6, 4, 1, 7
7	6, 4, 5, 7, 10, 9
8	1, 3, 5, 6, 8, 10
9	3, 4, 2, 1, 5, 9, 10
10	8, 10, 2, 4, 6
11	3, 1, 9, 5, 7
12	1, 9, 10, 2, 7, 8, 3
13	4, 3, 10, 2, 8, 6
14	4, 2, 8, 5, 1, 6
15	1, 5, 2, 6, 8, 3, 4,

4. THE PROPOSED SIMULATION MODELS

The proposed layouts were modelled using Arena software.

In the simulation model of functional layout, jobs arrive in the system randomly by the Create module. Then using the Assign module part types as well as parts sequences are determined. Part types are defined with general discrete distribution, DISC, which allows certain values with given probabilities. The part type assignment has two purposes; first is to define which part is arrived, and then part type value can be associated with the parts' sequences which were defined with Advanced Set and Sequences data modules.

Using the Leave module, different parts are transferred to their first work centre. The Leave module allows seizing the transportation resource, as well as considering the proper transfer time between different departments or workstations. Figure 1 shows the arrival logic.

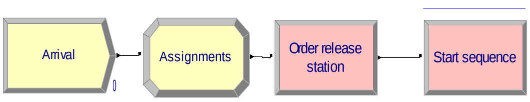

Figure 1: Arrival logic

Different departments possess different number of machine types although machine types are the same in each department or machine centre. When the jobs enter the appropriate department, based on the part sequence, first the transportation resource is released, and then they enter the department queue in case all the machine resources are busy. Next, because the entity can seize every each machine units in its current department, the Select Block module uses Preferred Ordered Rule (POR) to select and guide the entity to the first Seize

Block for which the required resource units, namely; operator and machine, are available. After the job receives the required service at the first department, in the Delay module, it runs through next department until it receives all the required processes and then it leaves the system. Figure 2 shows department four with four similar machines which are named as Process 1 to 4.

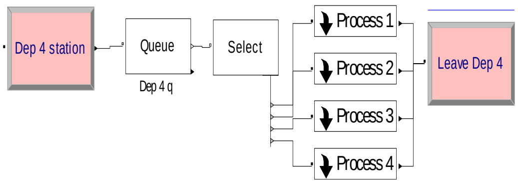

Figure 2: Machine centre logic in the FL

Regarding the setup reduction factor (SRF) logic, in each department, Process Submodels that represent work centre can intelligently diagnose if the two consecutive parts are similar or not. More precisely, after the part enters the Process Submodel, it enters the Seize Block module to grab the machine and operator resources. Then before it enters the Delay Module, the Decide Module checks and compares the part type of current entity with the last part type that left the existing Process Submodel. When any entity goes through any Process modules, Assign modules allocate its part type value to the multi-dimensional Last Part variable which allows comparison of two consecutive entities' attributes by the successive Decide Module. Then, if two consecutive parts are similar, the setup reduction factor can be assigned to the entity by the successive Assign modules. In other words, if the machine has already been setup for that similar part type, setup time can be reduced by setup reduction factor at the Delay Module. Finally, the entity releases the seized resources at the Release Module and proceeds to its next location on the basis of its predefined sequence. Figure 3 illustrates the component of a Process Submodel.

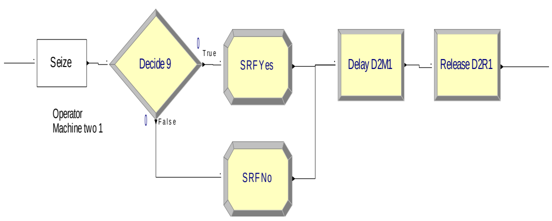

Figure 3: The Process submodel logic

The simulation models in this study only assume unidirectional flow of materials and backtracking is not allowed. Also because setup times are not provided in the case study of (Co & Araar, 1988), setup times are supposed to be 10 percent of the parts' processing times in the Delay Modules. The delay times that are defined by equation 5, includes SRF, setup and processing times. Obviously, this equation states that the pure value of process time is 10 percent less than the values presented in the table 1 in order to consider this 10 percent as the setup time. Then, again the actual processing time is added to the setup time which is multiplied by the value of SRF.

$$Delay\ time = (\,Process\ time\ -\ (\,Process\ time\ *\ .1)\,)+\ (\,Process\ time\ *\ .1\ *\ SRF\,) \qquad (5)$$

Similar to functional layout, cellular layout model consists of three main parts: jobs arrival, cells and exit logics. The cellular model consists of 64, machines which are distributed unevenly between 6 cells. Like functional layout, part types go through different machines based on their defined processing plan by the Sequence Data module. In the CL, part travel within and between cells which necessitates consideration of inter-cell and intra-cell travel time definition .

In contrast with the functional layout in which each department had one queue, in the cellular simulation model, each machine centre has its own queue. All of CL's queues are governed by the same priority rule of first in first out (FIFO). In the FL the travel time only included inter-cell travel time, however, in the CL, parts can travel within and between cells which requires the definition of both inter-cell and intra-cell travel time.

Some features of the cellular simulation model are almost similar to functional layout. Therefore, to be brief the explanations of these features are not repeated here. For example, the similar logics include job arrival; exit the system, transfer logic and process submodel.

Simulation model of Fractal layout is more complicated than last two models. The part routing information of FrL was not presented in the original design of FrL, therefore, the responsibility of determining parts' sequences are creatively assigned to the developed simulation model of this layout. This must be expressed so that this logic is based on the capability of each fractal to process all part types. In order to achieve this purpose, parts sequences are not assigned to entities in the arrival logic; however, it is allocated when jobs arrive in a chosen fractal with lowest number of entities in its queues. In other words, when initially jobs arrive into the system, their part types are allocated to them and then they seize the transportation resource to travel to the fractal cell which has the lowest number of parts in its queue, see Figure 4.

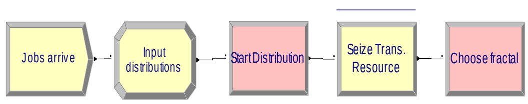

Figure 4: Arrival logic in the fractal layout

Selection of the proper fractal cell is carried out by the PickStation Advanced module. This module is used to choose a fractal cell with the lowest number of entities in its queues and then send the job to that chosen fractal.

Equation 6, which calculates the total number of entities in the queues of each fractal, is used in the Pickstation module.

$$\sum_{i=1}^{n} NQ\ (QM(i)) \qquad (6)$$

Where

- NQ is the number of entities variable, in a queue
- QM (Queue machine) denotes the queue name of machine i.

When the parts are sent to any particular cell, their sequences are assigned to them firstly. Then they are guided to their first work centre by the Route transfer module. Afterwards they follow their sequence until they receive all the necessary services by the Enter and Leave transfer modules in that particular fractal. Figure 5 shows the station of fractal one and necessary modules to route parts based on their sequences.

Figure 5: Fractal station

Due to the fact that each fractal can process all part types, inter-cell movement is not allowed. Also each part types process plan follows the shortest distance travel rule within each fractal. Other logics of fractal model like machine centres and exit are similar to models of last layout types.

4.1. Models Verification

The three developed models were comprehensively verified by using numerous Arena verification techniques. These techniques include;

1 using the Check Model Command
2 overcrowding the systems for a large period of time and observing some performance measures like; queue length and output quantities
3 Most importantly, using the Command window and the trace command while only one entity was allowed to enter the system.

4.2. Experimental Design

The variable input factors or experimental factors include SRF and the three proposed layouts. While layout factor consists of three levels, SRF includes two levels of high and low. Table 4 shows the experimental factors and their description.
Fixed factor elements of this simulation study are also summarised in table 5.
In this case this simulation study consists of 6 different alternatives (Scenarios) as shown in table 6.
As the quantities of inputs and outputs can be the variables of economies of scale and scope measures. Table 7 represents the chosen performance measures of this simulation study.

Table 4: Summary of experimental factors

Factors	Levels	Description
Layout type	Functional Cellular fractal	Three layouts were explained and depicted in previous section.
Setup Reduction Factor (SRF)	Low	SRF= .8
	High	SRF= .2

Table 5: Fixed factors of the simulation study

Characteristics	Value
No. of Part types	15
No. of machine operators	67 in FL 64 in CL 33 in FrL
No. of transportation resource	infinite
Job inter-arrival times (minute)	Expo (3)
Transfer times (minute)	
Inter-cell	UNIF (1,15)
Intra-cell	UNIF (1,5)
Process times	Shown in the table 3
Queue ranking rule	FIFO
Replication length	1920 hours (one year)
No. of replication	100

Table 6: Features of different scenarios

Scenario	Layout type	SRF
1	Functional	0.8
2	Cellular	0.8
3	Fractal	0.8
4	Functional	0.2
5	Cellular	0.2
6	Fractal	0.2

Table 7: Performance measures

Performance measures	Input / Output
Operator working time	Input
Transportation working time	Input
Machine working time	Input
Material quantity	Input
Product types Produced	Output

4.3. Results and Analysis

There was a huge results generated from this research work which will be presented in the conference. However, Figure 6 shows the output quantity of different part types in the six different scenarios under investigation. The most striking feature of the obtained results is that the outputs of all scenarios follow the same pattern and this is due to the part mix probability distribution used in the three layouts. Additionally, the recorded highest output quantity was belongs to FrL with high SRF. Then the figure indicates that at same value of SRF allocated to the three layouts, FL and FrL had the lowest and the highest output values respectively. Finally, it is obvious that the output values of FrL with low SRF is considerably close to the output values of FL with high SRF. This can be interpreted as a higher efficiency of FrL compared to other layout types. Due to space limitation, the other four performance measures under investigation in this research work will be presented in the conference.

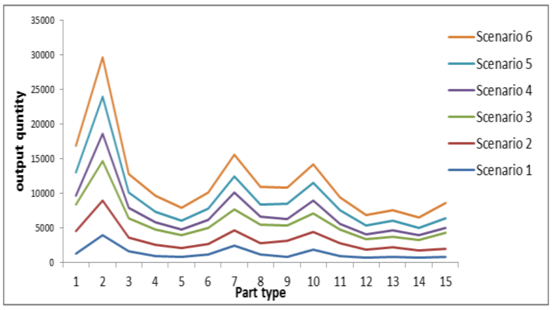

Figure 6: Output values of different scenarios

There were five performance measures considered in the analysis, it was clear that the FrL layout outweigh the other two layouts in transportation time, operator working time and output values. While FL performed better than FrL and CL in terms of machine working time. On the other hand, it has been found that the fifth performance measure, materials quantity that arrives to the system, was at same level for all the three layouts.

5. EFFICIENCY ANALYSIS

"DPIN™ software is used for decomposing Productivity Index Numbers into measures of technical change and various measures of efficiency change" (O'Donnell, 2011). This software can analyse the productivity of any multiple-input multiple output firm working in any market environment (O'Donnell, 2011). According to (O'Donnell, 2011) DPIN can generate measures of numerous efficiencies, including; residual output-oriented scale efficiency (ROSE), residual input-oriented scale efficiency (RISE) and residual mix efficiency (RME) which are measures of productive performance associated with economies of scale and scope (EoSS).

After inserting the performance measures (input and output values), which were resulted from simulation study, into the DPIN software, scores of various efficiencies were generated. This efficiency analysis was conducted based on Constant Returns to scale (CRS) assumption. Also regarding the orientation of the efficiency analysis, input-oriented approach was chosen for this analysis.

As mentioned before, the RISE and RME values of DPIN output file can be used to represent scores of scale and scope economies, respectively. The score of scale and scope economies of different scenarios as well as the maximum efficient scenario under CRS assumption is clearly illustrated in table 8.

Table 8: Results of efficiency analysis under CRS

Scenario	level of scale economies	level of scope economies	Max
1	0.8893	0.8893	
2	0.9181	0.9181	
3	0.9952	0.9952	
4	0.8888	0.8888	
5	0.9679	0.9679	
6	1	1	✓

Therefore, from table 8 the followings can be concluded;

1. The highest degree of productivity, due to EoSS, is achieved by the FrL with high SRF. This indicates that when FrL's input is increased, the output will also increase by same rate.
2. Even FrL with low SRF shows a higher level of scale and scope efficiency than the bests of FL and CL. The quantity of this difference is approximately 11 and 3 percent in relation to FL and CL respectively.
3. Different values of SRF influenced the EoSS of FL, CL and FrL by almost 0.1, 5 and 0.5 percent respectively. This finding complies with the previous studies which mentioned the SRF as the main advantage of group technology (Chtourou, et al., 2008).
4. All in all, it was observed that the FrL showed higher level of EoSS related efficiency than that of CL; similarly CL had higher degree of such efficiency than FL.

6. CONCLUSION

This study focused on benchmarking of the Economies of scale and scope (EoSS) of three different layouts which was functional, cellular and fractal layouts. In order to achieve this goal, detailed simulation models of these three manufacturing layouts were developed. Although layouts' configurations of this simulation study were adapted from the valid designed layouts available in the literature, the part routings of designed FrL was not available in its original paper. Therefore, based on the characteristic of FrL, the assignment of part sequences was creatively defined by advanced modules of Arena. Then simulation models of this study were comprehensively verified. In addition, consideration of statistical concepts in the experimental design has led to the generation of statistical reliable performance measures with short interval values at 95% confidence level. These statistical valid performance measures were used in the efficiency analysis of the mentioned layouts included in the benchmarking.

The generated performance measures from simulation study have shown different superiority-inferiority results in different layouts. While FrL with high SRF could produce the highest output production, CL and FL possessed the second and third highest values of the output production. Operator and transportation working time were at their lowest level in the case of FrL while CL and FL stood in the second and third positions, respectively. Moreover, SRF did not dramatically influence the value of machine working time within same layouts configuration. The results also showed that for same number of parts produced using FrL, we need almost 17% extra in machine working time if FL used.

Measures of scale and scope economies were calculated by DEA LPs and Constant Returns to scale (CRS) assumption. Regarding different models of DEA; input oriented CRS was found appropriate for the purpose of this study. Nevertheless, the efficiency analysis under CRS model identified the FrL with high SRF as the most efficient firm, in comparison with FL and CL. This efficiency analysis also proved that FrL outperformed both CL and FL in terms of EoSS efficiency score, regardless of SRF.

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