Throughput Analysis for Manufacturing Serial Systems using Discrete-Event Simulation and Analytical Calculation

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https://sriopenjournals.com/index.php/engineering_technology_review/index

Citation: Vanasarla, H. & Tang, H. (2022). Throughput Analysis for Manufacturing Serial Systems using Discrete-Event Simulation and Analytical Calculation, Engineering & Technology Review, 3(1), 15-28. Doi: https://doi.org/10.47285/etr.v3i1.117

Research Article

Abstract

In this paper, throughput analysis is studied by employing different industrial factors like reliability, buffer system, cycle time, and production time in the manufacturing workstation's layout. The research investigates the variations in throughput with both DES simulation and analytical methods by allocating different inputs. The results of analytical calculations and DES model throughputs are close, which explains the framework applying the production line cases that are proved effective to the system reliability challenge of serial manufacturing for increasing performance. The different inputs are selected based upon the real manufacturing layouts.

Keywords: Workstation, Production Effectiveness, Serial Manufacturing, Reliability, Cycle Time, Buffer.

1. Introduction

1.1 Background

With the start of industry 4.0 programs, the idea of intelligent production has gained significant attention between researchers from academia and industries. Especially, data-focused knowledge acquisition prototypes are now considered an important pillar for smart manufacturing. The concept of intelligent manufacturing methods has the opportunity of system difficulties and emphasizes that systems must be designed to be durable to unexpected circumstances and to forecast trends in real-time for large quantities of data. In recent times, the concept of smart manufacturing is developing with different strategies to overcome the challenges.

However, some tasks require the experimental efforts of the representative to create a more suitable vision for the world. Especially to meet with the requirements of superior reliability and integrated analysis, guarantee, and the optimization liable for the lifespan of design, production, and handling. Products are the output of the manufacturing process, which is the implementation form of the manufacturing system. Therefore, the reliability of the final produced throughput is related to the coherence of the manufacturing system and the overall quality of the production process. Generally, still, great design cannot ensure that produced products achieve satisfactory reliability if the design quality of the production system is poor. Therefore, incorporating the reliability development and optimization for manufacturing systems is crucial to assure the output.
1.2 Literature Review
The Fourth Industrial Revolution is the constant automation of conventional manufacturing and manufacturing practices, using modern technology. Large-scale machine-to-machine interaction and the internet of things are incorporated for improved automation\[16\], enhanced interaction and self-monitoring, and fabrication of smart machines that can analyze and identify issues with no human intervention. However, in the real world, we find a product layout that refers to a manufacturing system for a particular product or part, where the work stations and equipment are along the line of production, as is the case with assembly lines\[14\]. Generally, jobs/parts will be moved along a line (not essentially a geometric line, can be of inter-linked work stations) with storage or conveyor(buffer)\[8\]. Work/job can be divided into small quantities at each of the workstations in the line to accomplish the throughput \[4\]. In the manufacturing process, jobs move from one workstation to other where the parts are moved in sequence until gets final finished products. The modernized production layouts are set up into different workflows like U-shaped configuration, a straight-through (or an I-shape flow) is often the finest flow pattern for a lengthy process, L-shaped flow configurations may work best for square-shaped when several similar process lines are nested together. There are other well-known workflows that are also categorized into series and parallel manufacturing layouts. Serial production \[5\] is industrial mass production. It is a method used in the manufacturing of jobs in series made in the same way. In mass production jobs, the manufacturing process is in constant motion between each production position. The difference between mass production \[17\] and serial production is the continuity of the work. With mass production, the manufacturing of products is carried out continuously, there are no production breaks. Serial production is arranged, so that product is moved sequentially from one workplace to another one. It is likely to adjust the production machines \[13\] to produce a new product. From a reliability \[3\] point of view, a series system is such, which fails if any of its elements fail. All these elements are thus arranged in series. If failure of any component does not depend on any other component, the reliability of the system is obtained simply as the product of the reliabilities of individual elements. The buffer stations or conveyors in between the workstation do not have any significance when the workstation fails but help to load the feed into the process. Here, the study considered the belt conveyor types. It moves parts from one end to the other, typically moving the belt across a supporting steel plate so that as the belt moves it slides. These conveyor belt types are called roller belt style or roller conveyor belt \[19\]. Speed can be variable with a variable speed drive.

a. A discrete-event simulation (DES) models\[6,9\] the technique to create a chain of events in time for a system as a (discrete). Every event happens at a specific time and shows a system change. Among sequential events, the system is not changed in the assumed events. Thus, the simulations can instantly leap in the timing of the next occurrence, this is called the next-event time cycle.

b. The analytical model \[7\] is mostly mathematical or computational and signifies the system in terms of numerical equations that indicate parametric connections. This is typically done by developing the fundamental guidelines to foresee how well the system performs.

In the next sections, DES and Analytical concepts are clearly defined to understand the motive of the paper and its analysis.

1.3 Motivation and objective
This study performs analysis with the conception of the real-time production layout case studies with series workflow by factors: reliability, buffer station, cycle time, and production time. In this study, key performance indicators (throughput, profit, and cost) have been studied with both methods that are by DES simulated and analytical models (calculated by developed equations). Since there are several challenges that might face expanding manufacturing operations or dealing with an increase in orders. Inventory is one problem, which is the reason for the running out of space inside the plant. But it does
not mean that we should immediately look for another manufacturing facility to meet needs. The best solution is to optimize the space inside the plant by having a good manufacturing layout.

At present trends, optimization of manufacturing layout is based on the software evaluations, which can be used to estimate the frequency of transit, material flow distances, and costs by using several software tools that help to measure the throughput. But many of the industries cannot use the software trends to measure the throughput. The objective of this paper is to prove approximate resemblances between the software and analytical calculations. The next sections will concentrate on the design and analysis of the manufacturing layout by using both the DES model and the analytical method (using the developed equations). Based on the production case study with certain limitations, which are discussed further.

2. Methodology

2.1 Manufacturing System Layout

Usually, an effective Manufacturing plant Layout has inventory, raw materials, workers/staff management, warehouse, quality checks, Power Source, and packaging. The allocation or designing of the workstations and buffer stations is significant to optimize space along with throughput/efficiency. For most industrial operations, the goal is comparatively simple to build a lean manufacturing system to reorganize production and to guarantee a smooth flow of work, raw material, and info.

In this case study, the serial production layout \[^{[12]}\] Fig. 1 is assembled by a series of workstations with machines, loading, and unloading processes internally. Where the external buffers \[^{[15]}\] and controls are responsible for throughput. However, reliability of the above all factors is necessary for system efficiency and WIP quality.

![Fig. 1 Internal and external buffers arrangement](image)

2.2 Considerations and Assumptions

Manufacturing/Production systems usually have four types of structural styles namely parallel, serial, series-parallel, and cycles that systems with rework measures. Those different structures can be modeled by production lines or network analysis, etc. This paper discusses the most common serial system structure, which is a representative structure to research the system reliability based on production effectiveness. This study researched the system reliability by using buffer's state into consideration and has effectively proposed the equal workstation by examining the relationship of states between machine or workstations and buffers, which guided comprehensive consideration of this research. Moreover, in this analysis to know about the effectiveness of throughput cost and results for throughput assumed 3K per unit and for the buffer, cost assumed $150k + 3k/unit.

The data is assumed approximately by using the input in regular intervals of time for normal and peak hours. The parameters of the model include manufacturing time of the jobs, time in queue, and time spent at each station. The wait in line system is defined based on the arrival time and manufacturing time. The arrival time is input, which is approximately assumed that jobs will arrive at different intervals of time for the DES model. At each station, the component arrival time is considered constant. The arrival time fits under processes that are assumed as rounded uniforms. The number of jobs at queue during the series manufacturing is queued in the buffer station.

The DES modeling is for simulating the arrangement of the manufacturing layout for the jobs to not wait in the queue or to avoid idle time for the reliability of production. In real scenarios, industries face breakdown or repair and quality issues. Although when the system effectively develops the specified
performance requirements, no repair is necessary or performed. So, the repair time factor is not considered for the study and the concept of the quality check or inspection is eliminated in this analysis because it is difficult to evaluate and design activity for the rejection and acceptance of parts. However, no defect parts are released without proper checks, nowadays because of automation work fewer defects are identified than in previous traditional production. Based on these assumptions' the layout is designed with few parameters for study.

2.3 Layout Configurations
The layout optimization for the 2 cases is constrained with the below parameters, as shown in Table 1 and Table 2. Further sections discuss the parameter's evaluation.

| Table 1 Parameter for L-B-L system (Case-1) |
|---------------------------------------------|
| No. of Workstations | 20 |
| No. of buffers | 1 |
| Buffer reliability | 100% |
| Workstation reliability | 91,94,95,96,99% |
| Cycle Time | 40,49,50,51,60 sec |
| Production Time | 26 weeks |
| Buffer Size | 1,2,3,5,10,15, and 30 |
| Types of systems | Single and double |

| Table 2 Parameters for (L-B-L)-B-(L-B-L) system (Case-2) |
|----------------------------------------------------------|
| No. of Workstations | 40 |
| No. of buffers | 3 |
| Buffer reliability | 100% |
| Workstation reliability | 98.5% |
| Cycle Time | 50 sec |
| Production Time | 26 weeks |
| Buffers Size | 5 and 10 |
| Types of systems | Single |
Iterated the system with different combinations using the above tables. Below case 1 and case 2 are the two examples that are created by using the above tabular columns.

**Case-1:** In L-B-L (Line-Buffer-Line) system, which means Line-Buffer-Line, consisting of 20 workstations and a buffer, where there are 10 workstations for the first line continued with buffer and 10 workstations. After analysis completed the production time for 26 weeks and 6 working days per week and 16 working hours per day. The workstation parameters are reliability and cycle time. Cycle time 49-50 secs. Reliability after doing some case studies finally took it as 98.5%. The buffer station parameters are reliability and buffer size. The reliability is fixed at 100% to improve productivity.

**Case-2:** (L-B-L)-B-(L-B-L) system presents a Line-Internal Buffer-Line – External Buffer – Line-Internal Buffer-Line. This system consists of 40 workstations and 3 buffers (2-Internal buffers and 1-External buffer). In the system, there are 10 workstations for the first line, an internal buffer, 10 workstations, an external buffer, 10 workstations, an internal buffer, and then 10 workstations. As mentioned in Case-1 the parameters are considered the same, only the internal buffer station size is 5. In the below paragraphs the simulation analysis of both cases is explained clearly.

### 3. Throughput Simulation Analysis

#### 3.1 DES Modeling

Model construction of SIMUL8 models is usually not based on software development or numerical data but is constructing models of company schemes on the screen. However, SIMUL8 fulfills a mutual boundary with Visual Basic that leaves room for the formation of innovative prototype features, which cannot develop using only the graphical boundary. SIMUL8 also supports its own recreation language created by Visual Basic called Visual Logic, which enables the user to execute the complete logic of the simulation. The layout of SIMUL8 also enables interaction with other software platforms, such as Microsoft Entry and Excel. And supports interaction with databases using SQL.

The simulation method is based on manufacturing layout with the imagination of real-time industrial inputs to outputs. The layout is generalized which consists of the workstation's arrangement to produce different jobs. The whole layout setup is perfect with workstation reliabilities, buffer station's reliability, cycle time, buffer size, warm-up period, and production time. However, to run the process model, simulation software instructions are assigned to understand the layout requirements. For example, "Distribution" instruction is required to set up the workstation cycle.

![Fig. 2 Model for a 20-workstation system](image)

The DES model is developed using the Simul8 software for a series manufacturing system as per Fig. 2 to estimate throughput with reference to reliability. Therefore, for most waiting line systems, discrete-event simulation is often used to analyze the functioning of a system. This defines the system, arrival and
service patterns, and other aspects of the system. The simulation model replicates the behavior of the actual system, and the results are statistically analyzed to determine system performance. Based on the above considerations and assumptions, the DES simulation models are designed and functioned further, which is discussed in Cases 1 and 2.

3.2 Case-1: L-B-L System
The system has a Start and Endpoint with 20 workstations, one conveyor (buffer station), a warm-up period is 30 mins per day, 6 days a week is working and the overall production time is 24 weeks. Even buffer reliability is frozen to 100% to improve the system performance for this model.

There are several characteristics of a workstation, and each feature has many levels. In this study, the two key characteristics, i.e. reliability and cycle time, are considered. In addition, the size of the buffer connecting segments varies. To study these factors effectively, a design of an experiment applies to this study. The three input factors in this study include workstation reliabilities, cycle time, and buffer sizes. To consider different situations, this study considers two sets of experiments, shown in Table 3. The output of experiments is the system throughput. Results were examined with all the combinations to achieve at least a target of 70% of throughput, which can be realistic statistics. Below Iteration-1 is simulated with a different set of combinations (Workstation reliability, buffer size, and cycle time) as follows.

| Table 3 Input Factors in Design of Experiment |
|-----------------------------------------------|
| Factor | Cycle time | Reliability | Buffer size |
|--------|------------|-------------|-------------|
| Set 1  |            |             |             |
| 40     | 91%        | 5           |
| 50     | 95%        | 10          |
| 60     | 99%        | 15          |
| Set 2  |            |             |             |
| 49     | 94%        | 5           |
| 50     | 95%        | 10          |
| 51     | 96%        | 15          |

**Iteration-1:** Now, Fig. 3 is simulated with a combination of workstation reliability 98.5% and buffer size 3 and cycle time 50 seconds for Case 1.

![Fig. 3 DES model for 20-workstation system](image)

Experimental results for different iterations with different combinations of cycle time, buffer sizes, and workstation reliability result in different throughput values as explained below.

After iteration to the cases with different parameters and checking, the simulation analysis reveals that the throughput is constant after buffer size 15. For validation and verification tried with many iterations with different combinations (cycle time, reliabilities, and buffer sizes). Fig. 4 is plotted between buffer...
size and its effect; it shows more clearly that from buffer size 10 the parabola curve line is trending constant straight which means after size 15 there is no effect. This outcome helps to understand investors/organizations, how to fix the buffer size based on the production rate and can also stabilize the investment over buffers.

For making further clarification again the system is set under different combinations to evaluate throughput effect along with size of buffer and reliability variation. Thus, results show that 98.5% workstation reliability gives good throughput with buffer size 10 (Fig. 4 shows the one combination iteration). So, no other combinations are used to iterate for the Case-2 condition. So, for the further cases, only 10 is reserved as buffer size.

Fig. 4 Buffer size vs. Buffer effect on system throughput

Fig 5 and 6 show the influences of the three factors in the experiments and the possible interaction of these factors. From the two Figures, the effect of buffer size is not significant. In addition, there are no significant interactions between buffer size and station reliability, and between buffer size and cycle time. So, buffer size is not used to calculate in analytical calculations.
After iteration to the cases with different parameters and checking in both simulation and Minitab. Fig. 4 reveals that the throughput is constant after buffer size 15 which means after size 15 there is no effect of the buffer. So, for the further cases, only 10 is taken as buffer size. From case-1 iterations and results, it is proved that 98.5% workstation reliability gives good throughput with buffer size 10. So, no other combinations are iterated in the Case-2 condition.

3.3 Case-2: (L-B-L)-B-(L-B-L) System
The system has a Start and an Endpoint with 40 workstations, one external conveyor (buffer station), and two internal conveyors (buffer stations). The warm-up period is set at 30 mins per day; the work time is 6 days a week and the total production time is 24 weeks. Even buffer reliability is frozen to 100% to improve the system performance for this model.
In this case, only Table 2 data is used for the simulation, no different combinations are tried. The Fig. 7 double size of the layout is modeled and simulated just to check the behavior of the system if there is a need for increasing production rate on sudden demand. This analysis helps customers to allocate the space for more workstations in crisis management without expanding.
Iteration-2: Here Fig. 7 40 workstation DES model is simulated with a combination of workstation reliability 98.5% and buffer size 10 and cycle time 50secs for case 1.

To compare the DES simulation output and analytical calculations output the analytical method was used to observe the close relation by the developed linear equations.
Warm-up time for the model was set to 30 mins in a day. The arrival rate from the simulation is assumed with the real-time manufacturing layout with the production time. shows the customer arrival from simulation, data is randomly considered according to production hours and approximate throughput. This helps to understand the production, which helps to understand the manufacturing reliability and profits.
This case study is simulated only to understand the throughput analysis when the layout is doubled than existing. This iteration is useful for analyzing when the situation is in sudden demand for high production or to increase more workstations inside the same layout space.

4. Throughput Analytical Evaluation

4.1. Analytical Method Process
Earlier it was more complex, predefined mathematical formulas do not exist for system performance measures. In a mathematical model, an optimization challenge is a problem of obtaining the optimal solution for all practical solutions.
Optimization challenges with continuous variables are known as continuous optimization, in which an optimal value from a continuous function must be found. They can include constrained problems and multimodal problems.

- The equations that are developed should be a satisfactorily detailed representation of the system.
- The study results are stated in terms of constraint values which are often functions of other parameters. The analysis results are shown in tables, plots, and other representations.
- Graphics form of analysis describes changes in the state of a system or other unit.
- The calculations below are computed for reliability and throughput attributes of a system can be calculated with the below assumption and normal theories. Reliability is calculated as an exponentially decaying probability function.

Here an analytical version can represent the values for the parameters that are a function of time. Reliability develops an exponential failure principle, which implies reducing the time duration that is considered for reliability calculations elapses. System reliability in the initial state of operation will be high but gradually reduce to its lowest level over time.

### 4.2. Equation progression

Considering the series production system, the below equations are developed.

\[
\begin{align*}
\text{Eq1} & \quad f(R) = (R)^n \\
\text{Eq2} & \quad f(CT) = ((R/CT) \times 1hr) \times (pt - C) \\
\text{Eq3} & \quad f(B) = 1 + (S)^n \\
\text{Eq4} & \quad TH = f(CT) \times f(R) \times PT
\end{align*}
\]

Where, \( f(R) \) = Function for reliability of Workstations, \( R \) = reliability of Workstation, \( n \) = No. of buffer stations; \( f(CT) \) = Function for cycle time, \( CT \) = cycle time, \( pt \) = Production time per day, \( C \) = Warm-up period, \( S \) = buffer size (added 1 to the \( f(B) \) equation3 which improves system throughput); \( TH \) = Throughput, \( PT \) = Overall production time.

The case study is solved with the above equations.

**Equation 1:** 
\[ f(R) = (R/100) \]

For Workstation reliability 96%,
\[ f(R) = (96/100) = 0.96 \]

**Equation 2:**
\[ f(CT) = ((R/CT) \times 1hr) \times (pt - C) \]
Substituting Eq1 below
\[ f(R) = ((0.96/50) \times 3600) \times (16 - 0.08333) = 1100.16 \text{ JP/Day} \]

**Equation 3:**
\[ f(B) = (S)^n \]
\[ (1.05)^1 \text{ (For buffer size = 5)} \]
\[ (1.10)^1 \text{ (For buffer size = 10)} \]

**Final equation:**
\[ TH = ((f(CT) \times f(R)) + f(B)) \times PT \]
\[ = ((1048.32 \times (0.96)) + 1.05) \times (26 \times 6) \]
**Throughput** = 157160.2032 jobs

The above equations are used to calculate throughput.
Therefore, to understand the variation between the analytical and simulation models, KPIs are measured, and results are compared.

5. Results and Comparisons

5.1 KPI Consideration
Key Performance Indicators (KPI) require to be fully linked to any business objective and it is essential to the organization's success. If not, the target fails to report business/profits or other outcomes. Aspects like income, time, and other resources that could potentially affect the industry profits. Below are a few factors identified which can show impact on business and throughput.

I. The number of jobs entering the system. The jobs that are entering the system and passing through workstation and buffer station, which is considered as the final throughput. Part/job delay at any workstation may lead to a decrease in throughput.

II. The efficiency of workstations and buffer stations. Workstation and buffer stations efficiency theoretically can be achieved, but it is practically impossible to calculate. So, break-down or repair of the workstation and buffer station are not considered because it is unmeasurable and difficult to generalize the case to case. In the simulation assigned workstation reliability from 96 to 99% and 100% reliability to buffer, based on assigned efficiency, throughput varies for both analytical and simulation software.

III. Throughput analysis in software approach and analytical approach. In times of output rate, it was noticed that sensible buffers offered the best performance. However, it was also discovered that sometimes an unbalanced allocation of buffers provided a performance that was not statistically inferior to that of a balanced line. In both processes, calculations are accomplished.

The changing expenditures are undetermined or not predictable, which usually transforms into sales, the cost of production, and possibly expenses. The above measured KPIs are explained in brief with different case studies and suggestions that benefit the customers.

5.2 Comparisons between simulation and analysis
a. **Software method:** The key concept of throughput analysis is investing judgments in conditions of their effect on the entire system, rather than on the specific area in which an investment is contemplated. The simulation method is based on manufacturing layout with the imagination of real-time industries inputs to outputs. The layout is generalized which consists of the workstation's arrangement to produce the different jobs. The whole layout setup is perfect with the workstation's reliability, buffer's reliability, cycle time, buffer size, warm-up period, and production time.

b. **Analytical method:** The overall system approach encouraged by throughput study utilizes an entire assumed cost and production cost proposals that are much utilized to units/jobs produced.

To understand both methods clearly, the Single and Double Systems are arranged for the experiments of the case studies. Cycle time has been assigned in two types of distributions: Fixed distribution and Normal Distribution to identify the KPIs in different circumstances.

5.3 Graphical Illustrations
To understand both methods clearly, the Single and Double Systems are arranged for the experiments of the case studies. Also, cycle time has been assigned in two types of distributions: Fixed distribution and Normal Distribution in the below tabular columns and graphs.

**Two subsystems:** In this system, there are 20 workstations in two subsystems with 10 workstations for each sub-system. In the simulation, consider 10 workstations as one group and the other 10 workstations as the other group forming two rows. Here also only the reliability formula f(R) is changing and no change in the other formulas (f(CT) and throughput) where "n" is a single system with two subsystems, "N" is the number of rows. In the formula, n = 1 as 10 workstations are taken as one group. Since there
are 2 rows in the system and each row has 10 workstations, the reliability of the workstation (0.94) is multiplied twice (which is N) each with power 1 (which is n) as shown below.

\[ f(R) = (R)^N = (0.94)^1 = 0.94 \]

### Table 4 Difference between throughput (simul8 to simul8) --- (Equation to Equation)

| Simul8 Throughput | Equation Throughput |
|-------------------|---------------------|
|                   |                     |
| THPUT SIM Fixed   | THPUT SIM Fixed     |
| 172403            | 172309              |
| 174237            | 174136              |
| 176036            | 175994              |
| 168915            | 168890              |
| 170753            | 170689              |
| 172509            | 172477              |
| 165642            | 165554              |
| 167404            | 167332              |
| 169132            | 169094              |
| THPUT SIM Normal  | THPUT SIM Normal    |
| 168472            | 168408              |
| 170270            | 170208              |
| 172027            | 171959              |
| 185144            | 185139              |
| 168896            | 168878              |
| 168066            | 168026              |
| 169387            | 169336              |
| 163685            | 163694              |
| 165440            | 165413              |
| THPUT EQU         | THPUT EQU           |
| 153594.959        | 153594.959          |
| 156880.320        | 156880.320          |
| 160200.447        | 160200.447          |
| 150523.060        | 150523.060          |
| 147571.628        | 147571.628          |
| 150728.151        | 150728.151          |
| 153918.076        | 153918.076          |
| THPUT EQU         | THPUT EQU           |
| 144379.262        | 144379.262          |
| 149056.364        | 149056.364          |
| 153792.429        | 153792.429          |
| 141491.677        | 141491.677          |
| 140055.578        | 140055.578          |
| 150716.580        | 150716.580          |
| 138717.330        | 138717.330          |
| 143191.743        | 143191.743          |
| 147761.355        | 147761.355          |
| THPUT EQU         | THPUT EQU           |
| 6.000%            | 6.000%              |
| 5.000%            | 5.000%              |
| 4.000%            | 4.000%              |
| 6.000%            | 6.000%              |
| 5.000%            | 5.000%              |
| 4.000%            | 4.000%              |
| 6.000%            | 6.000%              |
| 5.000%            | 5.000%              |
| 4.000%            | 4.000%              |

**Fig. 8 Simulation throughput for a single assembly line**

Here the graph (Fig. 8) shows the variations in results between a single system and double system by comparing equation throughput with model simulation throughput (Normal Distribution and Fixed Distribution).

In Table 4 the difference is calculated between two different systems (single system and two subsystems) within the results of simulation and within the results of the equation. The parameter used in the simulation is Normal distribution. As shown in the table, the differences are negligible for simulation results that are varying between -0.005% to 0.055%. The difference between the equations results are varying between 4.00% to 6.00%. But the results difference is more while comparing the simul8 and equation. Here, one point is obvious that two subsystems and single systems give the same throughput. Fig. 8 shows the variation in results in two subsystems between the throughput of equation and simulation for fixed and normal distributions.
Table 5 Difference between throughput (simul8 to Equation) ---(simul8 to Equation)

| Single system | Single system | Two subsystems | Two subsystems | Equation Throughput | EQU Difference |
|---------------|---------------|----------------|----------------|---------------------|----------------|
| THPUT SIM Fixed | THPUT EQUI | SIM Difference | THPUT SIM Fixed | THPUT EQUI | EQU Difference |
| 172403 | 1595943959 | 10.20% | 172309 | 144379282 | 16.12% |
| 174237 | 156880320 | 9.92% | 174186 | 143936304 | 14.43% |
| 179036 | 160200447 | 8.96% | 179994 | 153795249 | 12.61% |
| 168935 | 169923060 | 10.86% | 168899 | 141491677 | 16.22% |
| 170753 | 163472714 | 9.92% | 170689 | 146055578 | 14.43% |
| 172509 | 169994438 | 8.92% | 172477 | 150716580 | 12.01% |
| 165662 | 147571628 | 10.99% | 165534 | 138711330 | 16.21% |
| 167404 | 150718151 | 9.56% | 167332 | 143191743 | 14.42% |
| 169132 | 160904175 | 8.95% | 169004 | 147761353 | 12.61% |
| THPUT SIM Normal | THPUT EQUI | THPUT SIM Normal | THPUT EQUI | | |
| 168472 | 153954059 | 8.83% | 168408 | 144379282 | 14.25% |
| 170270 | 16880320 | 7.84% | 170208 | 140306304 | 12.43% |
| 172027 | 160200447 | 6.87% | 171899 | 153795249 | 10.58% |
| 165144 | 150513060 | 8.85% | 165139 | 141491677 | 14.32% |
| 168896 | 153472714 | 7.85% | 166878 | 146055578 | 12.47% |
| 168666 | 155994438 | 6.91% | 168615 | 150716580 | 10.62% |
| 161567 | 147571628 | 8.89% | 161536 | 138711330 | 14.53% |
| 163865 | 150718151 | 7.91% | 163804 | 143191743 | 12.52% |
| 165440 | 153918075 | 6.98% | 165413 | 147761353 | 10.67% |

**Fig. 9 Simulation throughput vs. analytical results**

**Single system:** In this system, the entire system is considered as a single group irrespective of the number of rows and number of workstations. Since it is a single system, the 20 workstations are taken as one group in the system. In the simulation, all the 20 workstations are taken into one group. Here, even though we have two rows, the entire system is considered single. In equations, there is change only in the reliability formula (f(R)) and no change in the other formulas f(CT) and throughput. It is calculated by taking the below formula where "n" is the single system which is taken to the power of reliability of workstation. In the formula n = 1 as it is a single system.

\[
f(R) = (R_1^n)^1 \times (R_2^n)^1 = (0.94)^1 \times (0.94)^1 = 0.8836
\]

Here the graph (Fig. 9) shows the variations in throughput results in a single system by comparing analytical throughput with model simulation throughput (Normal Distribution and Fixed Distribution). In Table 5 the difference is calculated between simulation results and equation results for two different systems. The parameters used in the simulation are normal distribution and fixed distribution. For a single system, the difference between simulation (Fixed distribution) and the equation is varying between 9% and 11%. For a single system, the difference between simulation (Normal distribution) and equation
are varying between 7% and 9%. For two subsystems, the difference between simulation (Fixed distribution) and the equation is varying between 12.6% and 16%. For two subsystems, the difference between simulation (Normal distribution) and the equation is varying between 10.5% and 14%. So, from the above four results, the single system with Normal distribution has less difference compared to the other results. Fig. 9 shows the variation in results in a single system between the throughput of equation and simulation for fixed and normal distributions. By above-collected data and considering the assumptions, the simulation process is done with Simul8 software. Below are the measured KPI (Key Performance Indicators) results.

6. Conclusion

In a manufacturing system, workstation reliability, cycle time, and other factors determine the system output, which makes the incongruity of the manufacturing company. So, a few investigations are made in this study to see the variations in output (throughput) to solve the problem of maximizing the performance of serial manufacturing. Therefore, the simulation study is made with discrete-event simulation and analytical analysis modeling for serial manufacturing systems. Below key points are identified in this study.

• There is no improvement in throughput after buffer size 15. This is a key factor for the customers to not invest in buffer size beyond the limit.
• Identified that throughput is effective for workstation reliability of 98.5% for the buffer station reliability 100%.
• In the analytical version, developed the equations to study approximate throughput variation.

This helps to scrutinize the output of the overall system in instant using no software. In addition, the benefit of calculating simulation and analytical results is to provide the company/industry with information to identify the required system changes which are needed for the interactions with the customer. Operational performance of the system is analyzed by altering the number of workstations and buffer stations, working hours and days in a week, cycle time, the efficiency of buffer stations, breakdown or repair of the workstation. In accordance with the proposed changes, management or the organization can evaluate the expected performance of the system. Additionally, measured numerical approaches can be adopted to maximize the performance of the serial manufacturing industry of essential items to maintain the input and output. This study is limited to small manufacturing industries. In the future, we may consider other mass-production industries. We may also consider the parallel manufacturing system for the analysis. So, a regular real-time manufacturing layout is considered including the buffer workstation.

Author Contributions: Hema Vanasarla proposed the idea, researched, and developed the outcomes, as well as wrote the paper. Herman Tang steered, analyzed the data, and provided the necessary sources for this study.

Conflict of Interest: The authors declare no conflict of interest.

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