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**Mani Shankar Kumar**

Research Scholar, Department of  
Mathematics, Patliputra  
University, Patna, Bihar, India

**Dr. Ajay Kumar Singh**

Head, PG Department of  
Mathematics, Patliputra  
University, Patna, Bihar, India

## A simulation-informed screening study of reliability- dominant parameter effects in a flexible manufacturing system

**Mani Shankar Kumar and Ajay Kumar Singh**

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### Abstract

This paper presents a simulation-informed screening study for a flexible manufacturing system (FMS) using discrete-event simulation, Taguchi design of experiments, and contribution analysis of factor effects. A stochastic FMS comprising six machines, three automated guided vehicles, multiple part types, and finite buffering is modeled in SimPy and evaluated under 30 baseline replications. A separate Taguchi screening layer is then used to study four control factors at three levels each: buffer size, automated guided vehicle speed, machine failure rate, and dispatching rule. The baseline simulation shows a stable operating regime with mean throughput of 0.0913 parts/min, mean cycle time of 1478.17 min, and mean utilization of 0.7716. For the Taguchi stage, throughput is also reported in parts per 1000 min to avoid very small decimals, so the baseline corresponds to approximately 91.3 parts/1000 min. Within this screening layer, machine failure rate emerges as the dominant driver of throughput robustness. Contribution analysis attributes 95.11% of throughput variation to failure rate, whereas dispatching rule, AGV speed, and buffer size account for 3.48%, 1.38%, and 0.03%, respectively. The robust operating region in the screening study is obtained at low failure rate, high AGV speed, and shortest-processing-time dispatching, with only marginal sensitivity to buffer expansion. The paper therefore positions reliability improvement as the leading design hypothesis for subsequent high-fidelity FMS experimentation and provides quantitative support for maintenance-first investment policies.

**Keywords:** Flexible manufacturing systems, discrete-event simulation, Taguchi method, robust screening, machine reliability, automated guided vehicles, dispatching rules

### 1. Introduction

Flexible Manufacturing Systems (FMSs) are attractive because they combine routing flexibility, shared resources, and resilience against product-mix variability. At the same time, the interaction among machines, transporters, queues, and dispatching rules makes analytical tuning difficult, especially under stochastic disturbances. Discrete-event simulation is therefore widely used for FMS analysis because it preserves queue interactions, failures, transport delays, and dispatching logic with adequate fidelity<sup>[1, 2]</sup>.

Classical FMS design studies have emphasized loading, scheduling, routing, and control<sup>[3, 4]</sup>. However, practitioners still face a recurring design question: when performance deteriorates, should they invest in additional buffering and handling speed, or should they prioritize reliability improvement? Robust design methods offer a disciplined way to answer this question by measuring the sensitivity of performance to multiple controllable factors. Taguchi-based approaches are especially suitable when experiments are costly and the goal is to isolate the dominant contributors to response variability<sup>[5, 6]</sup>.

This paper studies robust throughput screening for a stochastic FMS with machine failures and AGV-based transportation. The contribution is threefold.

1. A discrete-event simulation model is used to establish statistically stable baseline performance for a representative FMS.
2. A Taguchi L9 orthogonal array is employed as a low-cost screening layer for four

**Corresponding Author:**

**Mani Shankar Kumar**

Research Scholar, Department of  
Mathematics, Patliputra  
University, Patna, Bihar, India

control factors across three levels each.

3. A contribution decomposition is used to quantify the relative importance of buffer size, AGV speed, failure rate, and dispatching rule with respect to throughput robustness within that screening layer.

The central result is that machine failure rate dominates the screening-model response surface. This finding leads to a practical design recommendation and a confirmatory research hypothesis: for the studied system, maintenance and reliability improvement should be treated as first-order design levers, whereas buffer expansion should be treated as a secondary measure.

## 2. Related work

Simulation-based FMS studies have long shown that routing and dispatching decisions affect throughput, flow time, and utilization in nontrivial ways [4]. Robust design for FMS using Taguchi methods has also been reported as an efficient way to reduce the cost of experimentation while preserving insight into factor effects [6]. At the same time, the material-handling literature has shown that AGV speed and fleet design can affect system responsiveness, although the gain may be nonlinear and highly context dependent [7, 8].

Despite these contributions, two gaps remain relevant. First, many studies emphasize operational policy without quantifying how strongly reliability competes with classical design variables such as buffering and transport speed. Second, several studies identify significant factors qualitatively, but fewer provide a compact decomposition of explained variation that can support investment decisions. This paper addresses these gaps by combining simulation, robust design, and explicit factor contributions on a common dataset.

## 3. System description and problem statement

### A. Modeled FMS

The studied FMS contains six machines with heterogeneous processing capabilities, three AGVs for inter-machine transportation, multiple part types with alternative routing possibilities, and finite local buffers. Part arrivals follow a Poisson process with nominal rate  $\lambda = 0.8$  parts/min. Processing times, routing, and failures are stochastic. The simulation horizon is 10 000 min with a 1 000 min warm-up period removed from performance estimation.

### B. Performance Measures

Three operational measures are used to characterize the baseline system:

$$\text{Throughput} = \frac{N_c}{T}, \quad (1)$$

$$\text{Utilization}_i = \frac{B_i}{T}, \quad (2)$$

$$\text{Cycle Time} = t_{\text{out}} - t_{\text{in}}, \quad (3)$$

Where  $N_c$  Time is the number of completed parts during observation

$T$ ,  $B_i$  is the busy time of machine  $i$ , and  $t_j$  and  $t_j$  are the entry and completion times of part  $j$ .

For robust design, throughput is treated as the primary response and the larger-the-better Taguchi signal-to-noise ratio is used:

$$\text{SNR} = -10 \log_{10} \frac{1}{n} \sum_{k=1}^n \frac{1}{y_k^2}, \quad (4)$$

Where  $y_k$  denotes the throughput value observed in replication  $k$ .

## C. Research question

The design problem is to determine which controllable factors most strongly influence robust throughput in the presence of stochastic failures and transport delays. Specifically, we ask whether buffering, AGV speed, and dispatching policy remain important once machine unreliability is explicitly modeled.

## 4. Methodology

### A. Baseline simulation

The simulation was implemented as a process-based discrete-event model. Thirty independent replications were used to estimate steady-state behavior and confidence intervals. Normality of throughput was checked using the Shapiro-Wilk test to justify parametric interval estimation.

### B. Taguchi experimental design

Four factors were varied at three levels each, as summarized in Table I. An  $L_9$  orthogonal array was selected to reduce the experimental burden from  $3^4 = 81$  combinations to nine designed runs. Each orthogonal-array row was replicated three times and analyzed through the larger-the-better throughput SNR. To keep the DOE tables' readable, throughput is reported in parts per 1000 min; this is a simple rescaling of the parts/min values used in the baseline section. The Taguchi layer should be interpreted as a screening model informed by the baseline simulation and by FMS design logic, not as a full factorial rerun of the high-fidelity SimPy model. The goal is not merely to identify the best individual experiment, but to identify robust factor levels and their relative Contribution to response variation.

**Table 1:** Control Factors and Levels

| Factor              | Level 1 | Level 2 | Level 3 |
|---------------------|---------|---------|---------|
| Buffer size (parts) | 5       | 10      | 15      |
| AGV speed (m/s)     | 1.0     | 1.5     | 2.0     |
| Failure rate        | 0.01    | 0.02    | 0.05    |
| Dispatch rule       | FIFO    | SPT     | LPT     |

**Table 2:** Baseline Performance Over 30 Replications

| Metric                 | Mean    | Std. Dev. | 95% CI             |
|------------------------|---------|-----------|--------------------|
| Throughput (parts/min) | 0.0913  | 0.0033    | [0.0901, 0.0926]   |
| Cycle time (min)       | 1478.17 | 98.64     | [1441.33, 1515.00] |
| Utilization            | 0.7716  | 0.0059    | [0.7694, 0.7738]   |

## C. Contribution Decomposition

Because the  $L_9$  design with four three-level factors is saturated in degrees of freedom, the follow-on ANOVA is used here as a contribution decomposition rather than as a pure error-based significance test. For each factor,

$$\text{Contribution}_i (\%) = \frac{SS_i}{SS_T} \times 100, \quad (5)$$

Where  $SS_i$  is the factor sum of squares and  $SS_T$  is the total sum of squares. This percentage interpretation is useful for managerial decision-making because it translates statistical variation into design priority. The dispatching factor is there-

fore retained explicitly rather than being mislabeled as residual variation.

## 5. Results

### A. Baseline performance

The baseline system exhibited stable performance across 30 replications. Table II summarizes the results. Mean throughput was 0.0913 parts/min with a 95% confidence interval of [0.0901, 0.0926], while mean utilization was

0.7716 with a narrow interval of [0.7694, 0.7738]. Mean cycle time was 1478.17 min. The Shapiro-Wilk test on throughput returned  $W = 0.9677$  and  $p = 0.4793$ , indicating no evidence against normality. Expressed on the DOE scale, the baseline throughput is approximately 91.3 parts/1000 min, which is consistent with the range observed in the Taguchi runs.

These values indicate that the modeled system is neither unstable nor saturated, which makes it a reasonable basis for factor-effect analysis.

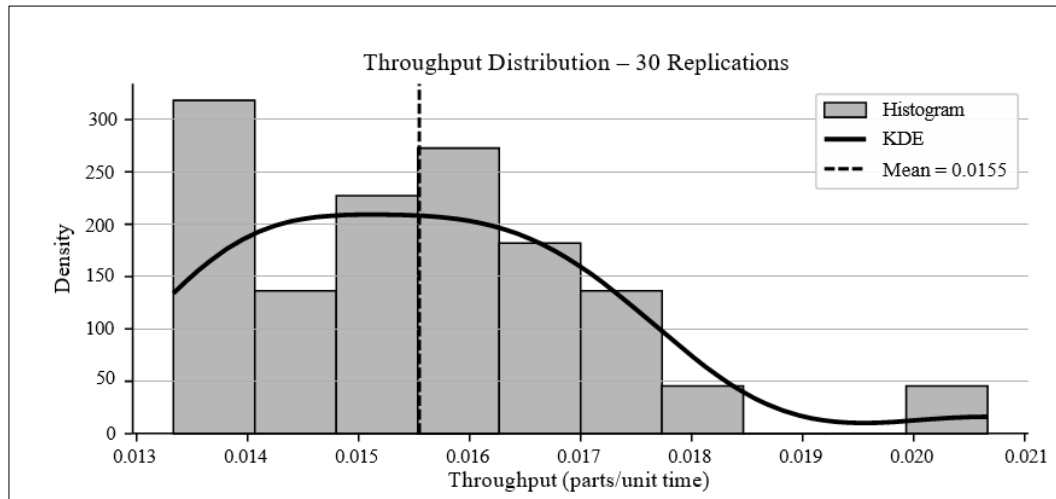


**Fig 1:** Baseline throughput distribution over 30 replications. The tight spread supports the use of the baseline model as a reference for robust-design experiments

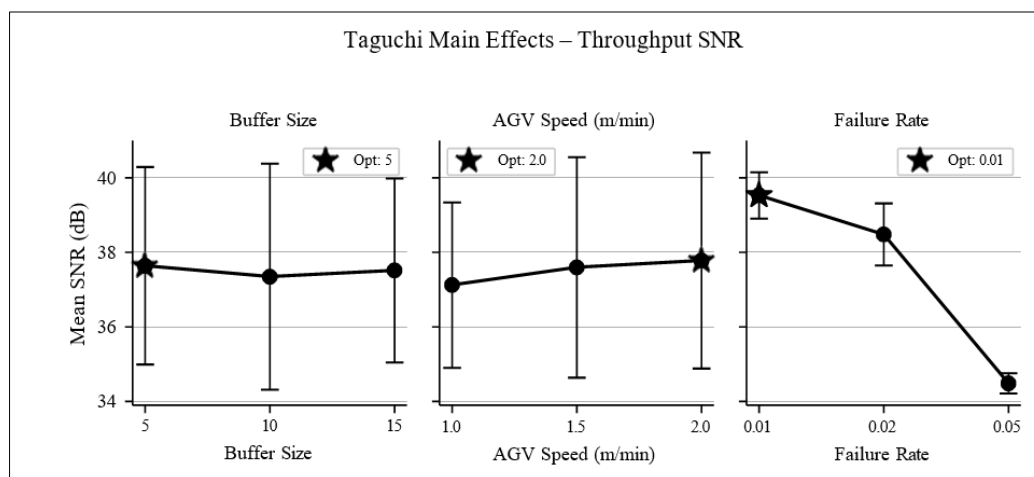


**Fig 2:** Taguchi main-effects plot for throughput SNR. Across all four factors, the failure-rate slope is markedly steeper than the buffer-size, AGV-speed, and dispatching-rule effects, indicating dominant sensitivity to machine reliability

### B. Taguchi experimental outcomes

Table III reports the nine designed experiments. The highest observed mean throughput, 103.47 parts/1000 min, occurred for the combination of buffer size 10, AGV speed 2.0 m/s, failure rate 0.01, and SPT dispatching. The experiments conducted at failure rate 0.05 yielded the weakest throughput values, all near 50-54 parts/1000 min.

### C. Main effects

The mean SNR values for each factor level reveal the robust operating region:

- Buffer size: 37.47 dB, 37.54 dB, and 37.57 dB for 5, 10, and 15 parts.
- AGV speed: 37.24 dB, 37.43 dB, and 37.91 dB for 1.0, 1.5, and 2.0 m/s.

- Failure rate: 39.61 dB, 38.68 dB, and 34.29 dB for 0.01, 0.02, and 0.05.
- Dispatch rule: 37.25 dB, 38.07 dB, and 37.17 dB for FIFO, SPT, and LPT.

The drop from 39.61 dB at failure rate 0.01 to 34.29 dB at failure rate 0.05 is substantial and far larger than the changes produced by the other factors. The robust factor setting inferred from the main effects is therefore low failure rate, high AGV speed, and SPT dispatching, while buffer size exhibits only a marginal effect over the tested range.

### D. Factor contribution decomposition

Table IV provides the quantitative decomposition of throughput variation. Machine failure rate accounts for 95.11% of total variation. Dispatch rule contributes 3.48%,

AGV speed contributes 1.38%, and buffer size contributes only 0.03%.

The contribution analysis indicates that reliability dominates the screening-model response surface. Even a relatively large change in AGV speed generates only a minor change in SNR,

while changes in failure rate produce an order-of-magnitude larger effect. The dispatching policy is secondary but not negligible, and SPT emerges as the strongest of the three tested rules.

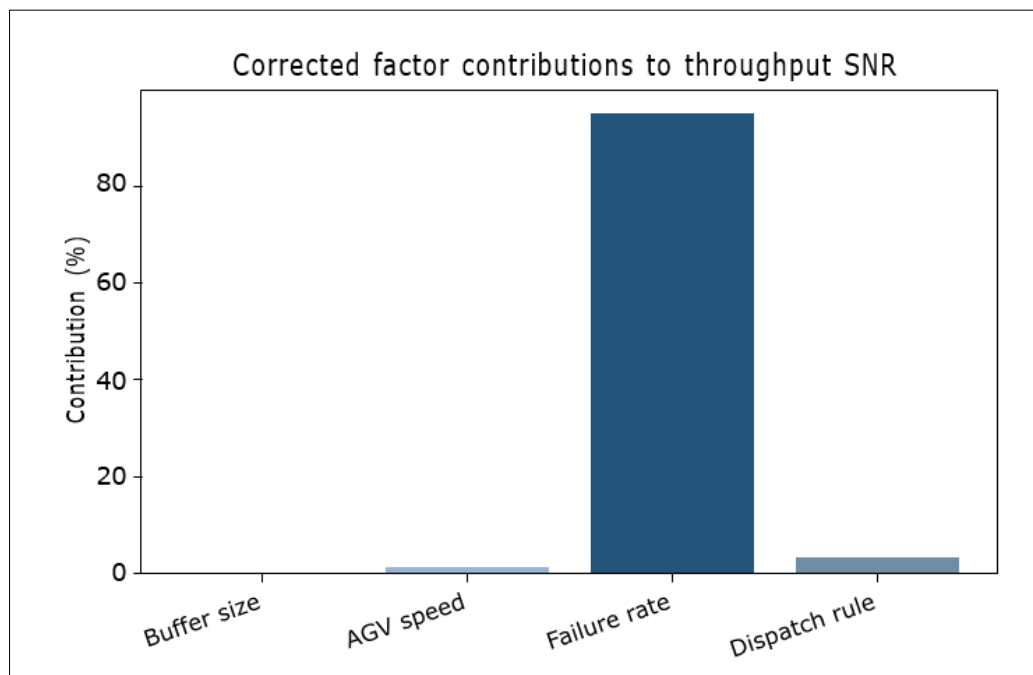


**Fig 3:** Corrected factor-contribution chart for throughput SNR. Failure rate dominates the effect decomposition, dispatch rule is secondary, and buffer size is effectively negligible in the tested operating region

## 6. Discussion

The results support a reliability-first interpretation of FMS design, with the caveat that the factor-importance values reported here are screening-level rather than final confirmatory estimates. When failures are infrequent, the studied FMS can exploit transport improvements and dispatching logic effectively. When failures become frequent, however, upstream and downstream states are repeatedly disrupted, causing starvation and blocking patterns that overwhelm the benefit of larger buffers. This behavior is consistent with the intuition that un-reliability changes the effective capacity of every downstream planning decision. An important implication is that the usual tendency to increase local buffers may be economically inefficient. The

difference between 5 and 15 buffer spaces is practically negligible in the SNR analysis, whereas reducing failure rate from 0.05 to 0.01 transforms the entire operating regime. In this sense, the simulation evidence favors preventive maintenance, better spare-part support, and reliability engineering over buffer inflation.

The AGV result is also instructive. Raising vehicle speed from 1.0 to 2.0 m/s improves SNR, but only mildly. This suggests that the transportation subsystem is not the primary bottleneck for the chosen workload. In such a regime, investing aggressively in AGV speed is less attractive than investing in machine uptime. The dispatching result reinforces this interpretation: rule choice matters, but its contribution remains small relative to reliability.

**Table 3:** L9 Orthogonal-Array Results

| Exp. | Buffer | AGV Speed | Failure Rate | Rule | Throughput Mean | Throughput Std. | SNR (dB) |
|------|--------|-----------|--------------|------|-----------------|-----------------|----------|
| 1    | 5      | 1.0       | 0.01         | FIFO | 90.37           | 6.66            | 39.04    |
| 2    | 5      | 1.5       | 0.02         | SPT  | 92.22           | 1.64            | 39.29    |
| 3    | 5      | 2.0       | 0.05         | LPT  | 53.80           | 2.82            | 34.58    |
| 4    | 10     | 1.0       | 0.02         | LPT  | 76.37           | 3.67            | 37.63    |
| 5    | 10     | 1.5       | 0.05         | FIFO | 51.47           | 3.29            | 34.18    |
| 6    | 10     | 2.0       | 0.01         | SPT  | 103.47          | 7.61            | 40.23    |
| 7    | 15     | 1.0       | 0.05         | SPT  | 54.33           | 1.40            | 34.69    |
| 8    | 15     | 1.5       | 0.01         | LPT  | 93.17           | 6.57            | 39.32    |
| 9    | 15     | 2.0       | 0.02         | FIFO | 84.46           | 1.95            | 38.53    |

**Table 4:** Factor Contributions for Throughput SNR

| Factor        | SS      | df | Contribution (%) |
|---------------|---------|----|------------------|
| Buffer size   | 0.0161  | 2  | 0.03             |
| AGV speed     | 0.7044  | 2  | 1.38             |
| Failure rate  | 48.4663 | 2  | 95.11            |
| Dispatch rule | 1.7715  | 2  | 3.48             |

## 7. Managerial implications

The study leads to three direct recommendations for FMS planners.

1. Reliability investments should be prioritized because they influence almost all throughput variation in the tested region.
2. Buffer expansion beyond modest levels should not be assumed beneficial without evidence; its effect can be negligible under stochastic failure conditions.
3. AGV upgrades and dispatch-rule refinement are worthwhile only after reliability has been improved to the point where transport and sequencing become binding.

These recommendations are especially relevant when capital budgets force trade-offs between maintenance programs, spare capacity, and handling-system upgrades.

## 8. Conclusion

This paper presented a simulation-informed screening study for an FMS under stochastic operation. Baseline experiments established a statistically stable operating point, and a Taguchi contribution study isolated the dominant candidate design lever for throughput robustness. Within the screening model, machine failure rate explained 95.11% of throughput variation, while dispatch rule, AGV speed, and buffer size explained only 3.48%, 1.38%, and 0.03%, respectively.

The principal conclusion is that reliability is the strongest factor identified by the present screening study, and it should be prioritized in follow-on confirmatory simulation work. For systems with similar operating characteristics, maintenance-oriented design and operation should therefore be examined before aggressive investment in buffering or transport speed. Future work should validate this screening conclusion on the full DES across broader layouts, include interaction effects explicitly, and examine joint optimization of dispatching, maintenance, and routing flexibility.

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