RECENT J. (2025), 75:107-113
https://doi.org/10.31926/RECENT.2025.75.107

# Analysis of Functional Blockages in Manufacturing Lines

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**Abstract**
Blockages in a manufacturing system can arise for various reasons and analysing them is crucial for improving efficiency and reducing downtime. In a simulation performed with Tecnomatix Plant Simulation, blockages can be analysed in several stages and from different perspectives, including identifying the causes and implementing solutions for process optimization. Functional bottleneck analysis in manufacturing lines explores the types of functional blockages that occur in production processes and their impact on efficiency and productivity. The study analyses how these blockages affect the flow of materials, and the resources used, providing solutions and strategies to minimize or eliminate them. The goal is to improve the overall performance of manufacturing systems and ensure smoother and more efficient production.

**Keywords**
simulation, bottleneck, buffer stock, theory of constraints, production productivity, workstation

## 1. Current State of Bottleneck Analysis in Production Systems

Bottleneck analysis in production systems is an active research area with numerous studies and methods developed to identify and address points of congestion that limit system capacity and efficiency.

Methods of detecting blockages:

⇨ Bottleneck detection methods can be divided into two categories: analytical and simulation based. Analytical methods assume that system performance is described by a statistical distribution, being suitable for long-term predictions.

⇨ Simulation-based methods are more useful for real production processes with complex structure and dynamics. Creating an adequate simulation model is time-consuming, but the results of the simulation experiments provide sufficient information to detect bottlenecks [3].

States of blocked and starved equipment:

⇨ Analysing the states of blocked and starved equipment is an effective tool to highlight and measure periods when equipment is either waiting for materials from previous processes (starved) or unable to transfer materials to the next process (blocked). This detailed examination helps manufacturers better understand their processes and identify optimization opportunities [6].

Comparative study of dynamic bottleneck detection methods:

⇨ A comparative study of dynamic bottleneck detection methods in serial production lines showed that different bottleneck identification methods lead to varying definitions of bottlenecks. The study compared three methods: Bottleneck Walk (BNW), Active Period Method (APM), and an adaptation of Interdeparture Time Variances (ITV). The APM and ITV methods had the highest agreement rate, while pairs with BNW had significantly lower agreement rates [1].

The specialized literature provides few, incomplete, and sometimes erroneous information about the mathematical model of bottlenecks in production systems. Most of the time, these focus exclusively on rigid manufacturing systems [1]. From the general conclusion resulting from the current state of research, it can be stated that the influence of refusals in operation on the efficiency of machine systems is significantly reduced by the following measures:

- Any blockage requires storage, with reserve stock, which becomes necessary on any technological line.
- On rigid/semi-rigid/manual/mechanized/partially and fully automated flow lines, the stocker can be stationary - placed on the floor, mobile - conveyor type, placed on the floor or suspended.
- On numerically controlled machines, on machining centres, on flexible machining cells, and in flexible manufacturing systems, the stocker can be stationary - placed on the floor, mobile - robocar type or conveyor type on the floor.
- In assembly and mounting systems, storage is done either in stationary stockers on the ground, conveyor type on the floor or suspended, or mobile robocar type.
- In machine systems, storage necessarily requires sectorization.

## 2. Defining Disturbances in the Manufacturing System

Disturbances are random, uncertain, unpredictable events and, from a pragmatic point of view, impossible to forecast and pre-evaluate. They are objective and subjective delays, having natural or human causes in material processing, organization and management of processes, with negative effects of reducing the rhythms and levels in manufacturing processes. Disturbances cause the output quantity to vary independently of the variation of the input quantities (order).

In the cause-effect relationship, disturbances are caused by internal causes, with internal / external effect, called endogenous (internal) disturbances and similarly, disturbances with external causes, with internal / external effect, called exogenous (external) disturbances. The causes of exogenous disturbances are the market for finished products, that of resource suppliers (materials, production capacities, human resources, energy, etc.), supply, sale (delivery), etc. Those of endogenous disturbances are the manufacturing system and process, the organization of the manufacturing flow and managerial dysfunctions. On the other hand, the disturbances are functional and organizational. The functional ones have as their source the machine system and the organizational ones are of a managerial nature.

Disturbances in a manufacturing system refer to any unexpected events or factors that disrupt the smooth operation of the production process. These disturbances can cause delays, reduce efficiency, and negatively impact the overall performance of the manufacturing system. Common types of disturbances include:

- Machine Failures: Breakdowns or malfunctions of machinery that halt or slow down production.
- Supply Chain Disruptions: Delays or issues in the delivery of raw materials or components needed for production.
- Human Errors: Mistakes made by operators or workers that affect the production process.
- Quality Issues: Defects in raw materials or finished products that require rework or scrapping.
- Scheduling Conflicts: Overlapping or misaligned production schedules that cause bottlenecks or idle time.
- Environmental Factors: External factors such as power outages, natural disasters, or adverse weather conditions that impact production.

Effective management of these disturbances involves identifying their causes, implementing preventive measures, and developing strategies to minimize their impact on the manufacturing process. This can include regular maintenance of machinery, improving supply chain management, providing training for workers, and optimizing production schedules. By addressing disturbances proactively, manufacturing systems can achieve higher efficiency, better product quality, and increased overall productivity [2].

For this paper, internal disturbances are of interest. Internal disturbances have their causes in their own environment. According to most authors, internal disturbances are the causes (phenomena) that produce the variation of the system outputs for constant inputs over time. This means that the variation of the outputs is caused by internal causes of the system. Their effect consists in obtaining unwanted values of the outputs, different from the planned ones. To obtain the desired values of the functionals, the process of monitoring and correction of the disturbances must be executed.

As frequently mentioned in the specialized literature [5], the main difficulty in addressing bottlenecks lies in their dependence on a large number of random factors, often probable in number and influence. All existing theories currently treat bottlenecks with global, general methods, using aggregated parameters, without knowing the influence of the weight of different specific parameters on the system's output indicators. Additionally, the lack of knowledge in the field is often compensated by global monitoring and corrections on the system output, which are sometimes late and have disastrous economic effects.

## 3. Analytical Model of Blockages

The blockage of a workstation can have one or more sources, one or more causes. If all the causes and sources of a workstation blockage are allocated the meaning of "defect" and noted as *d*, then the number of sources and causes of a blockage will be noted as $n_{bdi}$ (number of causes/blockages, workstation *i*). If the duration of repairing a blockage caused by cause *d* is noted as $t_{bdi}$ (minutes/blockage, cause, workstation *i*), expressing the duration in minutes of repairing a blockage caused by cause *d* in the current workstation *i*, then the total duration of repairing a blockage caused by all $n_{bd}$ causes in the current workstation *i* will be given by the following relation:

$$t_{b_i} = \sum_{d=1}^{n_{bdi}} t_{bd_i} \qquad [\min / PL_i, \tau_f] \tag{1}$$

where $\tau_f$ represents the duration of operation without refusals in the functioning of the workstation.
If we consider the average duration of the blockage $\bar{t}_{bd_i} = ct$, then the total average time to troubleshoot a bottleneck will be:

$$\bar{\boldsymbol{t}}_{\boldsymbol{b_i}} = n_{bdi} * \bar{\boldsymbol{t}}_{\boldsymbol{bd_i}} \quad [\min / PL_i, \tau_f] \tag{2}$$

Blockages are unpredictable and random; therefore, they are treated probabilistically. The frequency of blockages depends on the two types of blockages. Thus, the concept of blockages frequency is closely related to the types of blockages mentioned. The frequency of long-duration blockages represents the upper limit of blockages, while the frequency of short-duration blockages represents their lower limit. The concept of blockage frequency is based on the structure of a rigid flow manufacturing line. Consider a rigid flow manufacturing line composed of $q_t$ workstations arranged serially, non-sectorized (without reserve stock). In such a manufacturing line, it is possible/probable for any workstation or multiple workstations to malfunction due to one or more sources/causes.

In the case of "upper limit" blockages, the semi-finished product is kept in the working device (station) while the blockage is eliminated, after which processing continues until the part is completed. The failure of any workstation blocks the operation of several stations on the line, at least those downstream. The probability that the workstation ii will fail during the cycle is noted as $P_i$, where qt is the total number of workstations, serially aggregated, on the line. The blockage of the current station, stopping all $q_t$ stations on the line where a semi-finished product is fully processed in a complete production cycle, the number of line stoppages in a complete production cycle is obtained by summing the probabilities of all $q_t$ workstations on the line [7]. This sum will be called the frequency (of stoppages) of long-term blockages per cycle and is expressed by the definition relation:

$$f_{bl} = \sum_{i=1}^{qt} P_i \tag{3}$$

In the case of "lower limit" blockages, it is considered that the defective workstation is the one where the semi-finished product is rejected, has material defects, is destroyed, or damaged, and consequently must be removed from the workstation to eliminate the blockage.

The frequency of short-term blockages (stops) is expressed by the definition relation

$$f_{bs} = [1 - [(1 - \prod_{i=1}^{qt}(1 - P_i)] \tag{4}$$

It follows that, for a serial reliability system, the availability of the machine system, defined as the probability that a semi-finished product will be processed without stoppages caused by failures, is given by the relation:

$$Disp_{SM} = \prod_{i=1}^{q}(1 - P_i) \qquad [\%] \tag{5}$$

By the unit duration of a blockage, it is understood to be the partial duration during the troubleshooting of the blockage that corresponds to a production cycle, in which a part is processed, and it will be denoted by $T_b$. This depends on the frequency and number of causes of blockages, the duration of troubleshooting a blockage, the type of blockage, and the number of workstations affected. Thus, the calculation relationships will be as follows:

- for long blockages,

$$T_{bl} = \sum_{i=1}^{q_t} (f_{bl} * \sum_{d=1}^{n_{bd}} t_{b_d})_{i,l} \tag{6}$$

- for short blockages,

$$T_{bs} = \{[1 - (1 - \bar{P})^{\sum_{i=1}^{q_t} p_{is}}] * \sum_{d=1}^{n_{bd}} t_{bd}\}_{i,s} \tag{7}$$

The performance indicators of a flow manufacturing line are the engineering indicators that show the efficiency of the system's operation [4]. Among them, the following indicators that express functionality will be used: real cycle period (Tr), the degree of utilization of the workplace and the system ( $\eta_{(t,z)}$), efficiency (E), availability (A), stock per flow (S), detectability (Def).

If $T_{ci}$ is the period of the technological cycle of manufacturing (technological tact of manufacturing) and $T_{bi}$- the duration of the blockage of the current workstation, the real cycle period of this workstation $PL_i$, will be:

$$T_{ri} = T_{ci} + T_{bi} \tag{8}$$

$$\eta_{uz} = (1 - f_{bs}) \qquad [\%] \tag{9}$$

$$E = \frac{T_c}{T_c + T_b} \qquad [\%] \tag{10}$$

$$Def = \frac{T_b}{T_c + T_b} \qquad [\%] \tag{11}$$

Sectorization means dividing the line into sectors and assigning each sector to a stocker so that at least some performance functions take acceptable values (efficiency, productivity, utilization to be maximized and stock per flow to be minimized), under acceptable production costs.

The main criteria for allocating workstations in a sector are: technological compatibility; minimal asynchronisms in operation and blocking times (minimizing asynchronisms); high and approximately equal utilization rates; workstations should be of the same type (either all manual, all mechanized, or all automated); technological operations performed in all sector workstations should be of the same kind (either all processing, all assembling, all welding, all mechanical, all hydraulic/pneumatic, or all electrical); workstations allocated to the same sector should, as far as possible, have the same probability of failure.

## 4. Case Study

The sectorization method will be applied to a flow manufacturing line for which the operating parameters given in Table 1. To increase the efficiency of the line, it is proposed to divide the line into 3 sectors and place two stockers between the sectors. The new configuration of the manufacturing line will be validated by simulation in the Tecnomatix Plant Simulation software. The manufacturing line is composed of 12 workstations, for which the task times are given in Table 1. During the manufacturing of 1500 parts, the line had a total downtime of 42 hours, the number of failures recorded at each station is in Table 1.

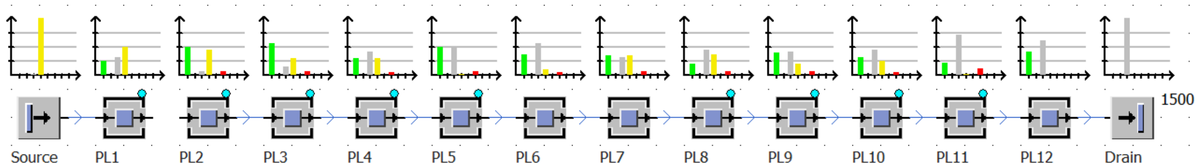
As can be seen in Figure 1, the workstations have a high degree of blockage, which leads to a low line efficiency of 50.42%.

To improve the performance of the manufacturing line, it is proposed to divide the production line into sectors, with storage units placed between them. These storage units will serve the purpose of delivering and accumulating parts when workstations within a sector break down.

The criterion for dividing the line is to achieve approximately equal blocking times per sector (Table 2). The manufacturing line will be divided into sectors according to Figure 2.

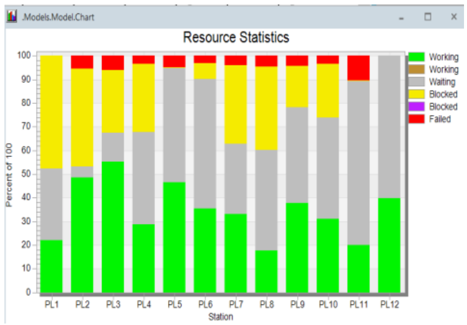
Table 1. Production line performance parameters

| PLi | $t_{opi}$ (s) | $n_{bdi}$ | $f_{bi}$ | $t_{bi}$ (s) | $T_{bi}$ (s) | E [%] |
|---|---|---|---|---|---|---|
| 1 | 30 | 0 | 0 | 630 | 0 | 50.42 |
| 2 | 66 | 15 | 0.010 | | 6.3 | |
| 3 | 75 | 18 | 0.012 | | 7.56 | |
| 4 | 39 | 23 | 0.015 | | 9.66 | |
| 5 | 63 | 25 | 0.017 | | 10.5 | |
| 6 | 48 | 9 | 0.006 | | 3.78 | |
| 7 | 45 | 27 | 0.018 | | 11.34 | |
| 8 | 24 | 47 | 0.031 | | 19.74 | |
| 9 | 51 | 30 | 0.020 | | 12.6 | |
| 10 | 42 | 21 | 0.014 | | 8.82 | |
| 11 | 27 | 25 | 0.017 | | 10.5 | |
| 12 | 54 | 0 | 0 | | 0 | |
| Total | 534 | Nb = 240 | 0.16 | | 100.8 | |




| Object | Working | Set-up | Waiting | Blocked | Powering up/down | Failed | Stopped | Paused | Unplanned | Portion |
|---|---|---|---|---|---|---|---|---|---|---|
| Drain | 0.00% | 0.00% | 100.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | |
| PL1 | 22.12% | 0.00% | 30.18% | 47.70% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | |
| PL10 | 30.96% | 0.00% | 43.05% | 22.67% | 0.00% | 3.32% | 0.00% | 0.00% | 0.00% | |
| PL11 | 19.90% | 0.00% | 69.46% | 0.32% | 0.00% | 10.32% | 0.00% | 0.00% | 0.00% | |
| PL12 | 39.81% | 0.00% | 60.19% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | |
| PL2 | 48.65% | 0.00% | 4.47% | 41.33% | 0.00% | 5.55% | 0.00% | 0.00% | 0.00% | |
| PL3 | 55.29% | 0.00% | 12.28% | 26.38% | 0.00% | 6.05% | 0.00% | 0.00% | 0.00% | |
| PL4 | 28.75% | 0.00% | 39.11% | 28.63% | 0.00% | 3.51% | 0.00% | 0.00% | 0.00% | |
| PL5 | 46.44% | 0.00% | 48.30% | 0.46% | 0.00% | 4.79% | 0.00% | 0.00% | 0.00% | |
| PL6 | 35.38% | 0.00% | 54.94% | 6.61% | 0.00% | 3.07% | 0.00% | 0.00% | 0.00% | |
| PL7 | 33.17% | 0.00% | 29.72% | 33.21% | 0.00% | 3.90% | 0.00% | 0.00% | 0.00% | |
| PL8 | 17.69% | 0.00% | 42.46% | 35.43% | 0.00% | 4.41% | 0.00% | 0.00% | 0.00% | |
| PL9 | 37.60% | 0.00% | 40.73% | 17.55% | 0.00% | 4.12% | 0.00% | 0.00% | 0.00% | |
| Source | 0.00% | 0.00% | 0.55% | 99.45% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | |

Portions of the States




| Name | Mean Life Time | Throughput | Throughput per Hour | Production | Transport | Storage | Value added | Portion |
|---|---|---|---|---|---|---|---|---|
| Part | 18:38.5379 | 1500 | 26.54 | 100.00% | 0.00% | 0.00% | 50.42% | |

Fig. 1. Production line simulation results - before sectorization

Table 2. Production line performance parameters after sectorization

| PLi | $t_{opi}$ (s) | $S_i$ | $n_{bdi}$ | $f_{bi}$ | $t_{bi}$ (s) | $T_{bi}$ (s) | E [%] |
|---|---|---|---|---|---|---|---|
| 1 | 30 | S1 | 81 | 0.054 | 630 | 34.02 | 50.42 |
| 2 | 66 | | | | | | |
| 3 | 75 | | | | | | |
| 4 | 39 | | | | | | |
| 5 | 63 | | | | | | |
| 6 | 48 | S2 | 83 | 0.055 | | 34.86 | |
| 7 | 45 | | | | | | |
| 8 | 24 | | | | | | |
| 9 | 51 | S3 | 76 | 0.051 | | 31.92 | |
| 10 | 42 | | | | | | |
| 11 | 27 | | | | | | |
| 12 | 54 | | | | | | |
| Total | 534 | | Nb = 240 | 0.16 | | 100.8 | |

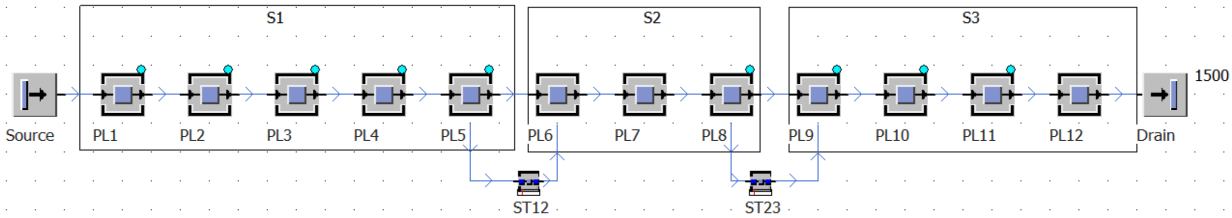


Fig. 2. Manufacturing line layout after sectorization

The simplified version of the layout according to Figure 3 was used for simulation, with the setting parameters from Table 2.

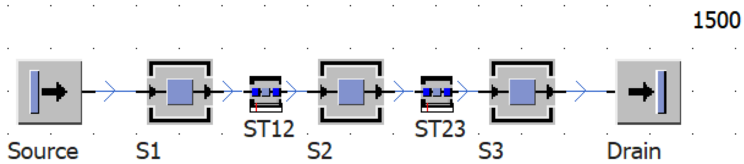


Fig. 3. Manufacturing line simplified layout after sectorization

By applying the sectorization method, the efficiency of the flow manufacturing line increased by 15%, in the improved version of the production line, the efficiency is 65.86% (Figure 4).

| Cumulated Statistics of the Parts which the Drain Deleted | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Object | Name | Mean Life Time | Throughput | TPH | Production | Transport | Storage | Value added | Portion |
| Drain | Part | 4:28.7582 | 1500 | 46 | 98.27% | 0.00% | 1.73% | 65.86% | |

Fig. 4. Production line simulation results - before sectorization

## 4. Conclusion

Any blockage, regardless of its nature, represents a disturbance in the manufacturing system and should be treated as such. Blockages negatively impact all performance functions, increasing the inventory in the flow and thus immobilizing part of the working capital; therefore, they need to be identified and managed. Financially, blockages are costly due to the expenses for their elimination, repair of equipment and facilities, and especially due to the losses caused by the failure to meet production delivery deadlines. Short blockages directly reflect the percentage of rejects, influencing the system's efficiency and wasting working capital. Long blockages, depending on their frequency and duration, the number of workstations, and the wear and tear of equipment, impact the structure, personnel qualification, and technical equipment of the maintenance system, which affects the maintenance and repair costs.

The blockage model is essential for design, operation, planning, as well as for maintenance and repairs, helping to structure the system, select machines, sectorize the system, choose and size inventories, supply spare parts, schedule repairs and production batches, and forecast rejects. The blockage model supports management in making decisions regarding planning the desired production and the delivered one, scheduling major repairs, structurally modifying the manufacturing system, identifying and eliminating the causes of significant financial losses, real-time monitoring of the manufacturing process, and ensuring product delivery according to the schedule.

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