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# IMPACTS OF MAINTENANCE POLICIES ON FRACTAL LAYOUT PERFORMANCE

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**Abstract**
Fractal cells were proposed to increase the flexibility of production systems and reduce production costs. Because all fractal cells comprise the same type of machine, they can manufacture any product type. Thus, product batches should not be moved on the factory floor. However, owing to natural wear and tear, machines must be stopped for maintenance, which requires machines from other cells, resulting in unnecessary travel. Therefore, this study aimed to investigate the impact of maintenance management policies on fractal physical arrangements using a simulation model. The results indicate that increasing the number of fractal cells can be advantageous for reducing product displacement and makespan.

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**Key Words:** Computer Simulation, Fractal Layouts, Maintenance Policies, Product Makespan

## 1. INTRODUCTION

One of the biggest challenges faced by manufacturing companies is their ability to serve a larger market at lower unit costs. To address this challenge, companies must develop physical arrangements capable of meeting these requirements. Four classic types of physical arrangements have been studied extensively: positional, product, process, and cellular, each of which is used for a specific purpose. For example, if the objective is to produce a small variety and a large volume, it is convenient to position the transforming resources in a sequence (U-shaped, linear, etc.) to guarantee an appropriate unitary flow (one-to-one). Therefore, the linear physical arrangements should be implemented. However, in traditional physical arrangements, the volume plays against variety.

In this context, various fractal physical arrangements have been proposed to satisfy both volume and variety requirements using fractal cells that are separated by corridors and feature the same types of machines. Thus, regardless of the requirements (variety, volume, etc.), a product can be manufactured in any fractal cell [1]. Each model imitates a production line, yielding higher productivity and lower unit costs.

Peralta and Soltero [2] reviewed the literature on fractal manufacturing system frameworks, which have been used for several years in many fields, such as supply chains, clusters between companies, quality control, and manufacturing. This study focuses on the use of fractals in terms of Industry 4.0, highlighting the main strategies and methodologies employed as well as successful case studies. The article ends by outlining the new challenges and adaptations required to follow the evolution of Industry 4.0, especially considering virtualisation using cyber-physical systems and sustainability requirements.

Peralta et al. [3] presented a conceptual model consisting of four principles for developing sustainable fractal manufacturing. The first principle addresses the requirements for managing chaotic environments. The second deals with organisational properties aimed at achieving certain objectives and the ability to self-organise and optimise. The third deals with the co-evolution of fractal organisations and product life cycles to ensure that the production system is sustainable. The fourth deals with the levels of fractal organisation, that is, how each should be structured at both the macro level (e.g., between companies and customers) and micro level

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(e.g., machines, products, and work strategy) to achieve the defined objectives of sustainable manufacturing. The proposed model was applied to a company to test its functionality. Peralta et al. [4] presented a bioinspired management model for increasing the sustainability of the fractal physical arrangement process.

Aririguzo et al. [5] obtained the best physical fractal arrangement using a GA. This study began with the cellular physical arrangement proposed in [6]. Using the crossover and mutation rules, the machine positions can be tested to minimise the total displacement. Thus, an optimal physical fractal arrangement was obtained.

Özkan and Ulutaş [7] used the concept of fractal physical arrangements to improve university office environments. They defined a series of numerical ergonomic criteria for the proposed mathematical model, including thermal comfort and seat position.

Montreuil [1] presented a more detailed discussion of the operation of fractal physical arrangements based on the issues of capacity planning, the creation of fractal cells, and production flow. They demonstrated the performance of the proposed fractal physical arrangements on a set of products listed in [6]. Tharumarajah et al. [8] discussed the development and operational characteristics of holonic, bionic, and fractal-physical arrangements.

Shih and Gonçalves Filho [9] presented a similarity-based procedure to improve the positioning of fractal cells. Although, by definition, all fractal cells have the same type of machine, depending on the company's financial situation, there may not be enough replicates to fill all the fractal cells. Therefore, the similarity between the fractal cells was calculated based on the type and number of replicas for each machine type. The authors suggested that the fractal cells with the highest similarity should be placed as far apart as possible.

Cha et al. [10] commented that fractal cells were developed to operate independently with their own goals, can self-adjust under uncertainties, and even function without human intervention. A series of decisions within each fractal cell can affect the functions of the cells and other cells. The authors suggested the use of decision fuzzification to improve cell communication and avoid conflicts.

Elaskari and Venkatadri [11] proposed the combined use of traditional and fractal cells over multiple periods. They claimed that if the efficiency of one cell increased (traditional cells), the flexibility of the other cells improved (fractal cells). Thus, a combination of both types of physical arrangements can increase the robustness of a production system.

Saad and Lassila [12] proposed a tabu search algorithm to better analyse the allocation of activities according to the production capacity of each fractal cell, with the aim of optimising product batch movements between cells. Finally, Jaegler [13] discussed the managerial difficulties faced by fractal organisations.

According to Elleuch et al. [14], the production system must be integrated with maintenance policies because they minimise the impacts caused by machine stoppages. To conduct the study, the authors studied the performance of traditional manufacturing cells, in which the machines were subjected to maintenance. Two cases (strategies) were considered: whether to send the batch to another cell or not because of maintenance. Batch sending can be unilaterally transferred, in which a batch is sent only from one cell to another, or bilaterally transferred. The authors observed that, in the first situation, only one cell increased the productivity and utilisation rate. However, an improvement was observed in both cells.

The stoppage of the machine during production should be considered, as it may generate several losses for the yielded units produced [15]. Rastgar et al. [16] declared that if maintenance is not included in production planning, machine failure may impact productivity and, in some situations, increase intermediate stock.

Studies exploring equipment failure and its impact on the performance of fractal physical arrangements are lacking. Most studies focused on developing a physical fractal arrangement based on the assumption that machines do not fail. Therefore, this study aims to evaluate the impact of different machine maintenance policies on production performance using this type of physical arrangement.

The remainder of this study is organised as follows: Section 2 presents the dynamics of fractal physical arrangements, considering maintenance stoppages, batch quantities that require movement, total distance covered, number of rejected parts, makespan, instants at which each batch arrives from another cell, and the instant at which this occurs. This section describes the methodology, materials, data, and experiments used in the study. Section 3 presents and discusses the results. Finally, Section 4 concludes the study and presents directions for future research.

## 2. MATERIALS AND METHODS

### 2.1 Working of a fractal physical arrangement

Consider a physical arrangement comprising three fractal cells with one operator per cell, as shown in Fig. 1. The list of products that the company receives is equally divided among these cells, regardless of the product type, because they all have similar conditions for producing unknown products [5]. This eliminates the need to visit other cells, thereby significantly reducing the number of batch movements between them. In this figure, the machine types are represented by numbers.

The distance between their centroids can be determined based on the established position of each fractal cell; thus, the pairs of fractal cells with the smallest distances can be determined. In this example, we assume, in a straight line, that $d_{min1\text{-}2} = 15$ distance units, $d_{min2\text{-}3} = 10$ distance units, and $d_{min3\text{-}1} = 20$ distance units.

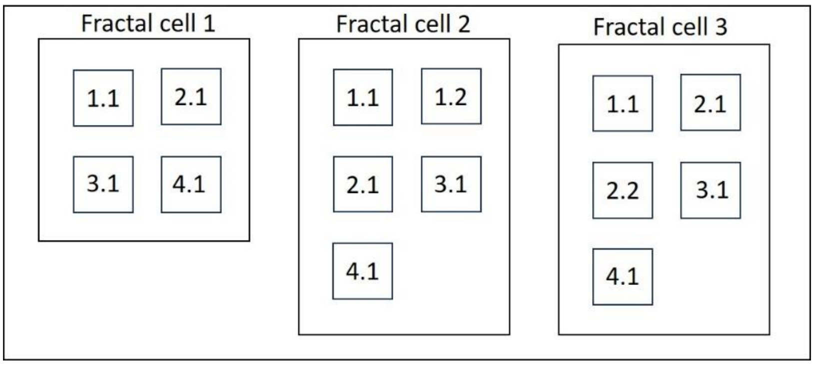

Figure 1: Example of a fractal physical arrangement with three fractal cells (the first number indicates the machine type, whereas the number after the decimal point indicates the number of replicas).

Table I lists the types of machines used and their maintenance information. A company can adopt three basic maintenance strategies based on interrupting production for maintenance more frequently for short durations or less frequently for longer durations.

The failure rate can be used to estimate the duration for which a machine must be stopped for maintenance purposes. For example, if a certain probability of failure predicts that a breakdown will occur in 200 s, the machine must stop for less than 200 s (preventive and predictive maintenance). In corrective maintenance, a machine is shut down only when a failure occurs, which occurs probabilistically based on the probability of failure, *pf*.

This example considers four types of machines with different maintenance strategies. Machines 1 and 2 involve preventive maintenance, whereas Machine 3 involves predictive maintenance, in which production is stopped once it produces a certain quantity or reaches a specific operating time without failure. Thus, it can anticipate failure and be considered predictive. In this example, it was assumed that Machine 3 was stopped after 50 s of operation, and Machine 4 underwent corrective maintenance.

Table I lists the maintenance cycles of machine types 1–4, including the downtime frequency and stoppage duration (maintenance duration).

Table I: Maintenance information for each machine type.

| **Machine type** | **Maintenance type** | **Fail probability** | **Maintenance cycle for** (s) | **Maintenance duration** (s) |
|---|---|---|---|---|
| 1 | preventive | *pf*1 | 100 (in use or not) | 40 |
| 2 | preventive | *pf*2 | 120 (in use or not) | 30 |
| 3 | predictive | *pf*3 | Operation for 50 s | 50 |
| 4 | corrective | *pf*4 | 200 | 90 |

Table II lists information on the products to be manufactured in each fractal cell. It presents the arrival times of the raw material batches, product type, operation sequence, duration of each operation (per unit), quantity of raw material in each batch, and total number of batches. Note that, as products arrive over time, it is not possible to place an advance order.

Table II: List of products to be manufactured in each fractal cell.

| **Arrival** (s) | **Product type** | **Operation sequence** | **Operation duration per item** (s) | **Quantity of raw materials per batch** | **Number of lots** |
|---|---|---|---|---|---|
| **Fractal cell 1** | | | | | |
| 0 | D | 4→1 | 10→50 | 3 | 2 |
| 20 | B | 2→1→4 | 10→15→10 | 4 | 3 |
| 35 | C | 1→3 | 20→50 | 5 | 1 |
| **Fractal cell 2** | | | | | |
| 0 | A | 4→2→3 | 20→40→50 | 3 | 1 |
| 25 | F | 2→1 | 10→30 | 2 | 2 |
| **Fractal cell 3** | | | | | |
| 0 | E | 1→2→ 3 | 20→30→20 | 2 | 2 |
| 30 | G | 2→4 | 50→20 | 2 | 1 |
| 40 | H | 4→1 | 30→20 | 1 | 2 |

Two cases are considered in this study. The first involves the movement of many batches between fractal cells owing to equipment maintenance. The performance of this case was compared with that of a case in which a batch waited in the same cell until maintenance was complete. The movement between the cells in this case was zero; however, a drastic increase in the total production time (makespan) was expected. Case 1 was selected for the following illustration. The difference in Case 2 is that the batch was reintroduced into the same cell.

A Gantt chart was constructed based on the information presented in Tables I and II. Fig. 2 shows the activity allocation for Product D at time 0. The second unit of the first batch of Product D was interrupted because Machine 1.1 stopped for maintenance, starting at 100 s and lasting until 140 s. At this point, only one unit was processed because both operations were completed for only the first unit of the raw material. To move Product D to the nearest fractal cell, Fractal Cell 2, the movement of the lots is expressed as 2 × 15 = 30 units of distance. The number of units rejected at this point was one, corresponding to a machine whose production is interrupted. There was no remaining list at time zero that required allocation to the Gantt chart, which recorded a total production time of 100 s. At that moment (100 s), the operator was available for the next product type (Product B). If the demand for Product B arrives at 150 s and another product batch arrives from another cell at 120 s, the operator processes the latter because the demand for Product B has not yet arrived. Hence, the arrival times should be arranged from shortest to longest. The x-axis always represents time.

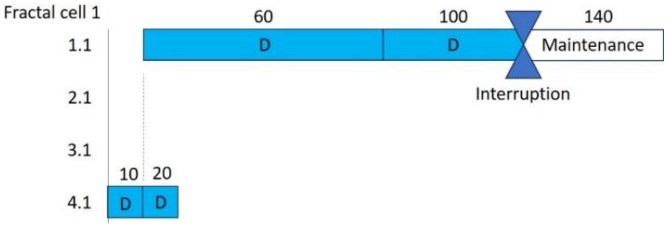

Figure 2: Task allocation for Product D, which is assigned to Fractal Cell 1 (a stoppage for preventive maintenance occurs at 100 s and lasts 40 s).

In Fractal Cell 2 (Fig. 3), Machine 3.1 was also unable to complete the last operation for the second raw material unit owing to maintenance, as it had already worked for 50 s (predictive maintenance). At this point, the total number of units produced was one. Additionally, a significant amount of material had to be moved to another fractal cell (Fractal Cell 3), which is closer and whose accumulated distance thus far is 1 × 10 = 10 units. There was no longer a list of products to be allocated at time zero. Product D only arrived in Fractal Cell 2 from Fractal Cell 1 at 100 s in two batches: one containing three units of raw material and the other containing one unit. Thereafter, the Cell 2 operator was available at 110 s for Product F.

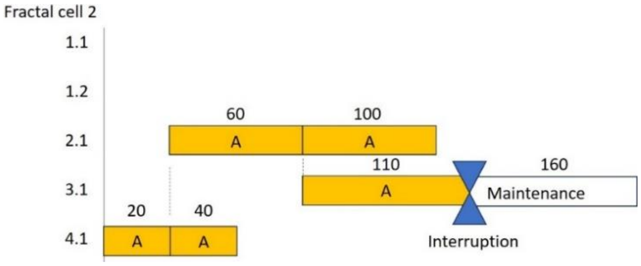

Figure 3: Activity allocation for Product A, which is assigned to Fractal Cell 2 (the stoppage for preventive maintenance occurs at 110 s and lasts 50 s).

For Fractal Cell 3, the first unit of the second batch of Product E is interrupted, as shown in Fig. 4. This is because Machine 3 completed 50 s of operation and was stopped for predictive maintenance. Because another Machine 3 unit (3.2) was available, it could be used. However, when the manufacturing of the second unit of the second batch began, Machine 2.2 underwent maintenance, indicating that this part could not be completed. At this point, only two units had been produced. The total number of lots to be moved to the nearest fractal cell (Fractal Cell 1) was zero; therefore, the displacement was zero. Additionally, the makespan was 120 s, and the number of rejected units was two. No remaining product list at time 0 required allocation to the Gantt chart. At 110 s, a batch containing one unit of raw material for Product A arrived at Fractal Cell 3.

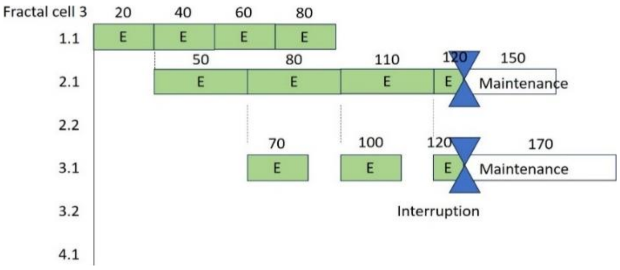

Figure 4: Activity allocation for Product E, which is assigned to Fractal Cell 3 (the stoppage for predictive maintenance occurs at 120 s and lasts 50 s).

Thus, this study aims to assess whether the difference between the makespan and batch displacement, as well as the number of rejected parts, can be reduced.

## 2.2 Research methodology

After understanding the dynamics described in the examples presented in the previous section, we determined the research methodology for the two cases considered in this study, as illustrated in Fig. 5. Elleuch et al. [14] argued that analytical models have proven that intercellular batch transfer improves cell availability; however, when used with large variations in production patterns, it becomes extremely complex. Therefore, a simulation was conducted in this study. According to Mares et al. [17], a model is an abstraction of a real system. Once the elements, relationships, and internal structure are defined, computer implementation permits obtaining results from several scenarios. The model was developed using the Pascal programming language and simulated in Dev-Pascal, which is freely accessible.

We obtained the makespan, total lot displacement between the fractal cells, and number of rejected parts. The simulation aims to verify the effects of product variety, batch size, operations (machines), number of operations, operating times, quantity of each machine type, number of fractal cells, maintenance duration, processing time until maintenance, and various failure probabilities on the performance of a physical fractal arrangement.

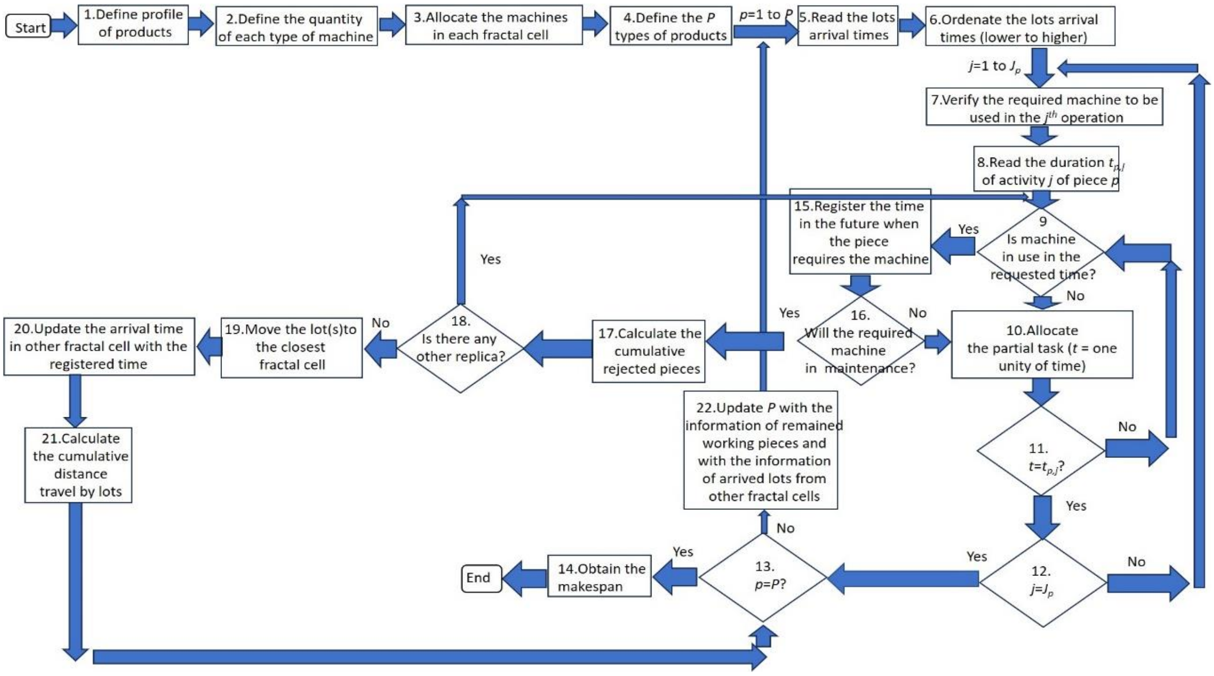

Figure 5: Research methodology for Case 1 (the variable *Jp* represents the number of operations on product *p*).

In Case 2, instead of updating the batch arrival time at another cell, it must be updated at the registration time in Step 15. In addition, it does not include Step 21. In Step 23, the number of batches and raw materials in each batch of the same cell are updated.

## 2.3 Input data

The number of fractal cells is related to the number of machines used. As all fractal cells must contain all machine types, this study established that the maximum number of fractal cells corresponded to the machine that presented the fewest replicates. For example, if a factory comprises 25 types of machines, one of which contains the smallest quantity (replicas) of the four units, then two (containing two units of the same machine in each cell) to four (containing a machine unit in each cell) fractal cells can be formed.

The input data used for conducting the computational experiments were defined based on the assumption that, although the products and demands are unknown, the production system has all the types of machines necessary to manufacture the products.

Several types of input data variables can be broadly classified as either uncontrollable or controllable. The uncontrollable variables include product variety, batch size, number of batches, times the demand arrives at the fractal cell, product listing size, number of operations, and operation duration. Product information refers to information determined by customers. A company that receives this information can organise itself to operate efficiently, which is why it is considered controllable. In this study, the controllable variables include the number of fractal cells adopted for product listing and the decision to send the batch to another fractal cell (Cases 1 and 2, respectively), as in Elleuch et al. [14].

The following were included as uncontrollable factors: 1) product variety = less than 100; 2) batch size = 10–50 units; 3) number of lots = 1–3; 4) product demand arrival interval = 10–50 min; 5) product listing size = 30 types of products; 6) number of operations = 1–5; and 7) operation duration = 1–5 min. Elleuch et al. [14] considered in their study two types of products for cell a (with three types of machines) and three types of products for cell b (with four types of machines). Moreover, fixed batches and only two traditional manufacturing cells were considered. Hence, our defined features accurately represent chaotic demand.

Each operation requested by a product differs from the others; that is, no operations are repeated. Table III lists the different types of machines considered in this study, followed by the replicates for each machine type. A significant challenge for companies is identifying how to organise themselves well in the face of unknown demands that vary considerably [2]. The addition of extra machines incurs high costs, which companies must avoid [18]. Therefore, the simulation did not aim to suggest adding more machines to the factory floor but rather to help companies that already have such machines adopt the best strategies regarding the number of fractal cells and whether to send batches between them.

Table III: Characteristics of each machine type.

| **Machine type** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **Total** | **Factory size** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Quantity** (number of replicas) | 3 | 4 | 3 | 3 | 4 | 4 | 3 | 4 | 3 | 5 | 36 | Small |
| | 5 | 6 | 7 | 5 | 8 | 7 | 5 | 6 | 6 | 5 | 60 | Average |
| | 8 | 10 | 9 | 10 | 11 | 9 | 8 | 9 | 6 | 10 | 90 | Large |
| **Maintenance type** | PR | PR | PR | PR | PD | PD | PD | PD | C | C | - | - |
| **Failure probability** | *X* | *X* | *X* | *X* | *Y* | *Y* | *Y* | *Y* | *Y* | *Y* | - | - |
| **Instance to start the maintenance** | ISPG | ISPG | ISPG | ISPG | ME | ME | ME | ME | IS | IS | - | - |
| **Maintenance duration** (min) | 5–10 | 5–10 | 5–10 | 5–10 | 50–100 | 50–100 | 50–100 | 50–100 | 50–100 | 50–100 | - | - |

*Legend:* PR (preventive), PD (predictive), C (corrective), ISPG (instance of stoppage), IS (instant of stop), ME (14,800 min earlier), *X* (1 stop in 6,480 min), *Y* (one stop in 64,800 min).

Thereafter, the process continues by selecting a fractal cell until all cells are allocated. This choice is factorial because five fractal cells indicate that there are 5! different allocation methods (instances). Once the sequence of the fractal cells is determined, their allocation follows the orientation established using a space-filling curve. This study employs a Moore spatial filling curve. Because of software limitations, machines of the same type located in the same fractal cell were used concomitantly in this study, simplifying Step 18 in Fig. 5.

This shows the types of maintenance required by each machine type, as well as their failure rates. Owing to the complexities associated with modelling maintenance procedures, this study employed the following conditions: a) a machine that is not in operation can also stop for maintenance; b) the elapsed time is computed (whether the machine is busy); and c) all machines have the same *pf*.

Pang [19] explained that fault predictions typically occur probabilistically. Bányai [20] cited the use of technology in a dynamic production process, where many real-time data could be retrieved. Hence, to improve fault prediction, Pang [19] suggested using an adaptive fault prediction model. However, maintenance information is unique for each type of machine and varies among companies. This implies that a fault maintenance model cannot be used. In this study, the machines considered work independently (i.e. not technology-connected) using simple technology. Therefore, we opted for a traditional one and the used information, which is shown in Table III. Torre et al. [15] reported that corrective maintenance costs were three to four times higher than scheduled maintenance costs. In this study, we assumed that the cost is ten times greater and is related to the time spent on maintenance (longer duration).

Assuming that common equipment fails after 45 days of operation, if a company operates 24 h a day, the chance of failure is 1 in 64,800 min. When this failure occurred, the outage lasted for 50–100 min. This information is used in the corrective maintenance model.

Instead, companies may choose to conduct short-term maintenance activities more frequently. Assuming that maintenance is conducted ten times more frequently than required (every 6,480 min), the maintenance time is reduced to 5–10 min. This information is used for preventive maintenance. Additionally, because predictive maintenance involves anticipating failure, maintenance should be conducted close to the failure time (14,800 min before the predicted failure, which lasts for 50–100 min).

## 3. RESULTS AND DISCUSSION

Tables IV and V present the statistical results of the simulations for Cases 1 and 2. Each row represents the number of cells stained. Owing to the limitations of the software used, only ten instances of fractal layouts could be simulated for each case.

Each instance executed in the model generated *n* values for the distances travelled (*n* corresponds to the number of fractal cells in the operation). The distance indicates the travel distance of batches from the original fractal cell to the nearest fractal cell. Notably, selecting the closest fractal cell does not indicate that all machines in it operate fully. This implies that even during batch movement, if the machine in the destination cell is undergoing maintenance, the batch is moved to the nearest cell. The sum of the distances of *n* cells is the total distance realised in the $i^{th}$ instance. The average of *i* instances can be calculated using their respective standards, as listed in Tables IV and V.

Additionally, ten makespans were generated for each instance executed in the simulation model (one for each machine type). The largest makespan represents an executed instance. Using these ten instances, the mean and standard deviation were calculated.

Finally, each instance produces rejected parts for each fractal cell. Thus, the sum of all the rejected parts from all *n* cells is the number of rejected parts in the $i^{th}$ instance. Using the information from all instances, the mean and standard deviation for all cells could be calculated.

According to Case 1, in small physical arrangements, using more fractal cells reduced the average batch displacement but increased the makespan. There was no perceived advantage in terms of the rejected parts, with variations in the number of fractal cells used. As expected, there was no displacement between the fractal cells in Case 2; however, the average makespan was higher than that in Case 1. In addition, the makespan did not vary with changes in the number of cells. According to Case 1, medium-sized companies are favoured when a higher number of fractal cells is used, as they can reduce the distance travelled by lots and the makespan. In Case 2, the intermediate use of fractal cells significantly increased the makespan, and the number of rejected parts was greater than in Case 1.

According to Case 1, large companies are also favoured with an increase in the number of fractal cells, the distance travelled, and the makespan (e.g., from two to three cells). An increase or decrease in the displacement was observed, and the same effect was observed for the makespan. The results of Case 2 show that the intermediate use of fractal cells should be avoided, as it increases the makespan, total distance travelled, and number of rejected parts.

Table IV: Statistical results obtained from the simulation for Case 1 (S.D. – standard deviation).

| S.D. of rejected pieces | Mean number of rejected pieces | S.D. of makespan | Mean makespan | S.D. of distance | Mean distance travelled | Number of fractal cells | Size of a company |
|---|---|---|---|---|---|---|---|
| 0.00 | 11.00 | 0.00 | 5440.00 | 0.00 | 149.39 | **2** | **Small** |
| 1.03 | 13.20 | 112.57 | 6240.80 | 10.93 | 80.15 | **3** | |
| 3.16 | 21.70 | 1008.59 | 12062.40 | 205.77 | 687.13 | **2** | **Average** |
| 0.74 | 7.90 | 898.12 | 11160.60 | 41.72 | 77.18 | **3** | |
| 12.26 | 65.80 | 3027.43 | 11019.60 | 107.56 | 230.96 | **4** | |
| 6.83 | 29.60 | 2443.66 | 10973.30 | 41.40 | 99.17 | **5** | |
| 3.83 | 22.70 | 888.05 | 9606.90 | 153.01 | 644.73 | **2** | **Large** |
| 1.15 | 8.00 | 598.58 | 8618.30 | 24.11 | 113.55 | **3** | |
| 11.71 | 61.00 | 1960.54 | 8104.10 | 170.83 | 383.18 | **4** | |
| 4.37 | 16.30 | 1689.57 | 8875.10 | 25.26 | 86.70 | **5** | |
| 5.10 | 33.30 | 2227.78 | 9149.10 | 37.64 | 140.37 | **6** | |

Table V: Statistical results obtained from the simulation for Case 2 (S.D. – standard deviation).

| S.D. of rejected pieces | Mean number of rejected pieces | S.D. of makespan | Mean makespan | S.D. of distance | Mean distance travelled | Number of fractal cells | Size of a company |
|---|---|---|---|---|---|---|---|
| 0.00 | 17.00 | 0.00 | 11733.00 | 0.00 | 0.00 | **2** | **Small** |
| 0.00 | 17.00 | 0.00 | 11275.00 | 0.00 | 0.00 | **3** | |
| 3.57 | 22.10 | 1284.28 | 14752.60 | 0.00 | 0.00 | **2** | **Average** |
| 1.07 | 8.60 | 407.34 | 11102.50 | 0.00 | 0.00 | **3** | |
| 57.01 | 332.50 | 16062.36 | 87697.80 | 0.00 | 0.00 | **4** | |
| 3.30 | 28.70 | 881.53 | 12231.60 | 0.00 | 0.00 | **5** | |
| 4.08 | 22.00 | 943.92 | 11496.80 | 0.00 | 0.00 | **2** | **Large** |
| 1.66 | 8.10 | 133.62 | 9453.20 | 0.00 | 0.00 | **3** | |
| 134.64 | 451.90 | 37143.24 | 119537.50 | 0.00 | 0.00 | **4** | |
| 2.23 | 11.00 | 327.63 | 10097.80 | 0.00 | 0.00 | **5** | |
| 4.57 | 30.70 | 899.41 | 10951.40 | 0.00 | 0.00 | **6** | |

Because the objective was to identify the configuration that reduces the difference between the makespans, distance travelled, and number of rejected parts, it can be stated that using more cells in small physical arrangements is optimal for meeting this objective.

It was expected that the larger the physical fractal arrangement, the smaller the makespan, owing to the increase in production capacity. However, this holds true depending only on the number of fractal cells adopted. Additionally, the results show that the strategy of expanding production capacity by acquiring more machines is not promising because the makespan is practically equivalent to that in smaller physical arrangements (as in Case 2).

## 4. CONCLUSION

This study aims to demonstrate the performance of fractal physical arrangements by considering the limitations of machine maintenance. We investigated possible strategies regarding the number of fractal cells and whether to transfer batches of raw materials used in the manufacture of products between the fractal cells. The simulation results indicate that the makespan tends to be higher if the company decides not to transfer product batches to closer cells. In general, if the makespan increases, the displacement decreases, and vice versa. The decision not to transfer lots promoted zero displacement. According to the simulations, depending on the number of fractal cells, the performance of smaller physical arrangements may be on par with that of the larger arrangements. Additionally, the Pascal programming language proved versatile as it was possible to model the conditions imposed by maintenance. Future studies should consider using other types of space-filling techniques, which would affect the distance covered. Finally, this study assumes that all machines can easily change their positions. In future studies, we will consider fixed machines and various part-order strategies.

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