Modelling and simulation of a coil manufacturing line using Petri Nets and Tecnomatix

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Abstract. This paper presents the modelling and simulation of an electric coil manufacturing line using two distinct methods: Petri Nets and Tecnomatix Plant Simulation. The aim is to evaluate the line's performance and identify opportunities for optimisation. Two simulation variants were developed for each method, using real operation times and the complete production flow. The results highlight significant differences between the two tools: Petri nets generated between 82 and 1352 parts, while Tecnomatix obtained between 159 and 1430 parts in the same working interval. The study demonstrates that optimising high-load cells (coiling, welding, testing) leads to major productivity gains and provides a solid basis for process improvement decisions.

Keywords: Coils, Modelling, Petri Nets, Simulation, Tecnomatix Plant Simulation

1. Introduction

Modern industry faces ever-increasing demands for greater efficiency, flexibility and reduced operating costs, prompting companies to adopt advanced methods of analysis and optimisation of production processes [1], [2], [3]. Discrete event industrial systems require careful management of the sequence of operations, synchronisation of resources and elimination of critical points, as these aspects directly influence the performance and stability of the manufacturing flow. In this context, modelling and simulation are essential tools, offering the possibility to analyse the behaviour of the technological line and evaluate alternative scenarios without additional risks or costs [4]. This paper analyses a manufacturing line for electrical coils, a product frequently used in electrical and electromechanical applications [5]. The coil manufacturing process includes operations such as winding, welding, assembly and final testing, each of which can become a critical point in the production flow depending on operational times and the capacity of the work cells. The analysis of these elements is necessary to identify areas of congestion and propose effective optimisation strategies [6].

Two complementary methods are used to carry out the study. The first method is based on Petri Nets, a well-established mathematical formalism for modelling discrete event systems, capable of explicitly rendering competition, conflicts and synchronisation between resources [7]. This formalism allows the analysis of the structural properties of the system and the evaluation of its behaviour in different operational scenarios. The second method uses the Tecnomatix Plant Simulation software platform, an advanced tool for simulating and optimising industrial processes. It allows the analysis of resource utilisation, blocking times, waiting times and general performance indicators, while also providing a detailed visual representation of the technological flow [8]. Through dynamic simulation, different scenarios such as doubling critical stations, redistributing operations or reconfiguring the flow can be quickly tested and compared. Two simulation variants were developed for each method in the study, using real operation times and the existing technological sequence. The main purpose is to evaluate the performance of the production line, identify critical points and establish optimal optimisation strategies. Comparing the results provides a complete picture of the advantages and limitations of each method in the analysis of real industrial processes.

2. Description of the production line

The analysed production line is designed for the manufacture of electric coils and is organised in a sequential technological flow consisting of several work cells. The process begins with the preparation of the conductor and continues with the winding operation, where the wire wound on the specific support according to the required number of turns shown in Fig. 1.

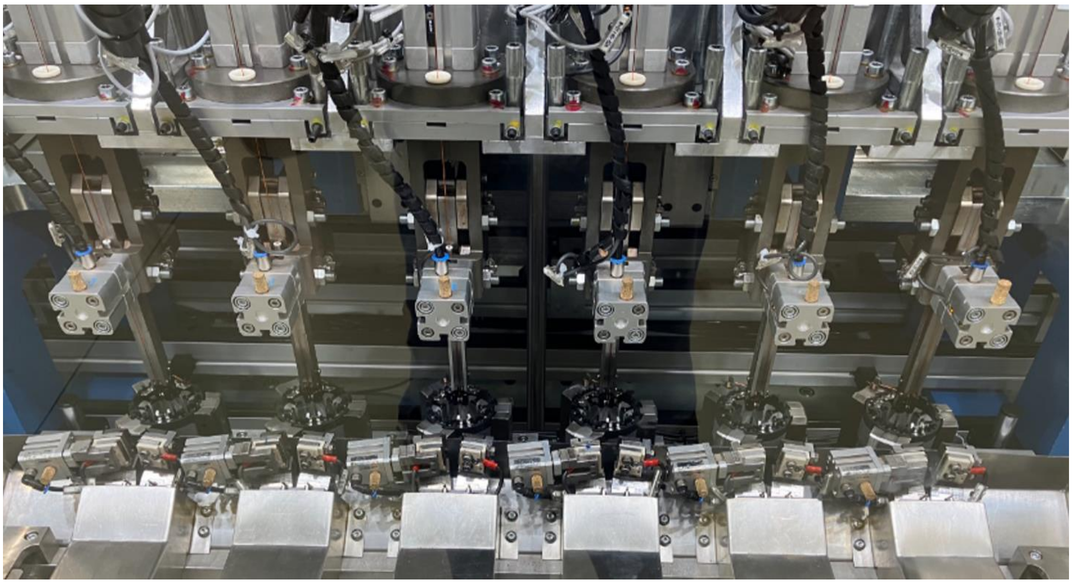

Fig. 1. Winding of 6 stator packages with 28 turns

The next step is to weld the conductor ends automatically to ensure electrical and mechanical connection. After welding, as shown in Fig. 2, the coil moves on to the next step of impregnation or code engraving, if required by the technological process.

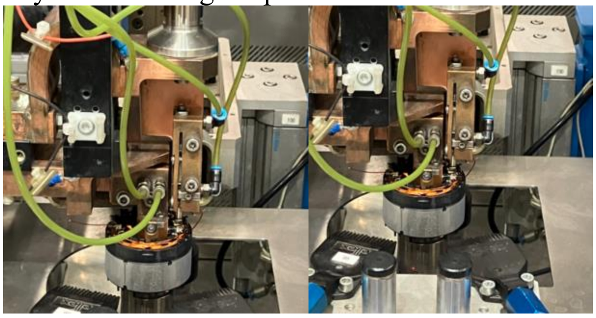

Fig. 2. Welding the coil contact pin using two welding robots

Finally, the product arrives at the test cell (EOL – End of Line), shown in Fig. 3, where the electrical parameters, continuity and final quality are checked. All cells are interconnected by a transport flow, and process times vary significantly between operations, which leads to critical capacity points, especially in winding, welding and final testing.

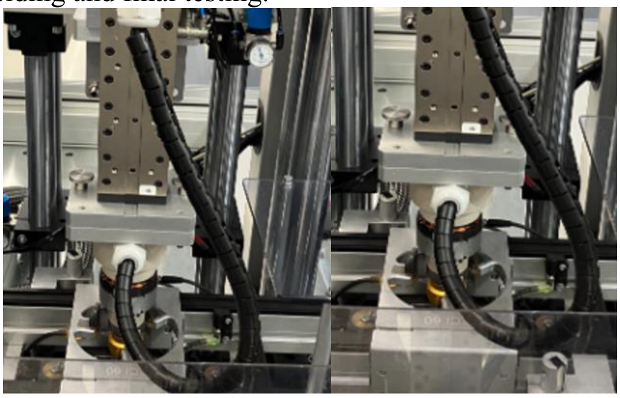

Fig. 3. EOL (End of Line) coil testing using two stations working

3. Manufacturing line modelling

3.1. Modelling with Petri nets

To evaluate the performance of the coil production line through mathematical modelling and simulation with Petri nets, two modelling variants were created. Table I presents the organisation of information for building the model in Petri nets

Table I.

Organisation Of Information For Model

No.	Description	No. Trans.	Description	Time
P1	Ready-made stator package	T1	Stator package loading	14 sec
P2	Confirm stator package loading	T2	Visual inspection of chamber 1	5 sec

No.	Description	No. Trans.	Description	Time
P3	Confirmation of visual inspection completed	T3	Stator package cleaning	8 sec
P4	Confirmation of stator package cleaning	T4	Stator package measurement	6 sec
P5	Confirmation of stator package measurement	T5	Disc assembly and stator package switching	12 sec
P6	Confirmation of disc assembly and stator package switching	T6	Inserting paper into stator package	14.5 sec
P7	Confirmation of paper insertion	T7	Assembling disc 2 and assembling on stator package	14.8 sec
P8	Disc 2 assembly confirmation	T8	Visual inspection of chamber 2	12 sec
P9	Confirmation of visual inspection 2 completed	T9	Stator package winding	180 sec
P10	Confirmation of stator package winding	T10	Coil welding	42 sec
P11	Coil welding confirmation	T11	Coil cleaning	6 sec
P12	Coil cleaning confirmation	T12	Cutting copper terminal wires from coil	14 sec
P13	Confirmation of wire cutting	T13	EOL (End Of Line) testing	24 sec
P14	EOL testing confirmation	T14	Coil cleaning	6 sec
P15	Confirmation of coil cleaning	T15	Coil evacuation	
P16	Counting completed coils			

In the first variant presented in Fig. 4, the line was simulated using Petri nets after inserting all the positions and transitions necessary to create this production line. We obtained the number of finished products resulting from the process, which was 82 coils. The low number of finished products obtained in the first simulation variant (82 coils) is due to the fact that the initial model of the production line has several structural and organisational limitations. In this configuration, each operation is performed only once, in a strictly sequential order, without parallel cells or additional resources to take over part of the load. The relatively long times of some operations, such as winding or welding, quickly lead to a bottleneck that slows down the entire flow.

Since resources are used successively rather than simultaneously, any delay at a single workstation propagates throughout the entire line [9], significantly reducing the production rate. In addition, the first option does not include optimisations such as doubling high-load cells, reducing idle times or balancing operations, which limits the total capacity of the line within a fixed time interval.

Thus, the productivity of only 82 reels reflects the operation of a line without optimisations, where the flow is restricted by the operational times of the cell with the longest duration, which dictates the pace of the entire process.

In the second simulation variant, illustrated in Fig. 5, a series of significant structural changes were made, aimed at eliminating the bottlenecks and imbalances found in the first configuration of the model. To this end, critical points in the flow were addressed by adding additional stations at Transition 9 (Stator package winding), Position 10 (Stator package confirmation) and Transition 10 (Coil welding). At the same time, functional improvements were implemented at Transition 13 (EOL testing), as well as adjustments to the operating parameters in the Transition 8 area, with the aim of increasing the robustness and continuity of the process.

These interventions aimed to redistribute the load between cells, reduce waiting times and increase the degree of parallelisation of operations, thus eliminating the bottlenecks that limited performance in the first variant. By increasing the operational capacity at the points identified as bottlenecks and improving the synchronisation between transitions, the production flow became significantly more stable and uniform.

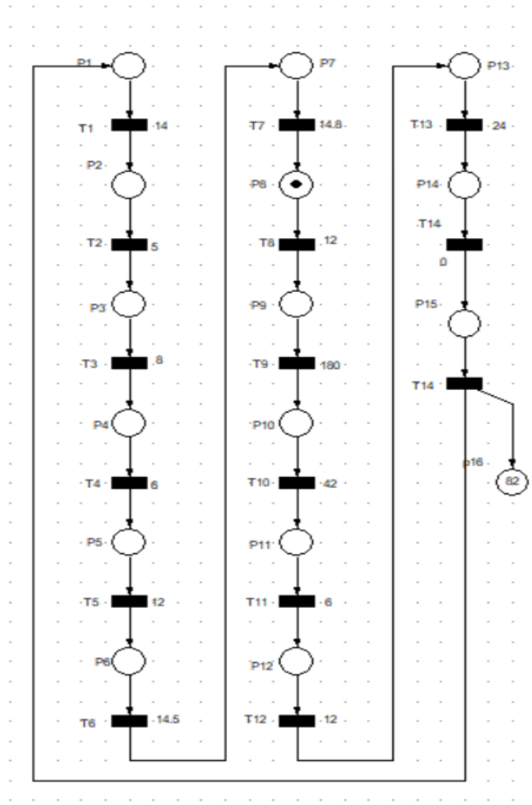

Fig. 4. Simulation variant I Petri nets

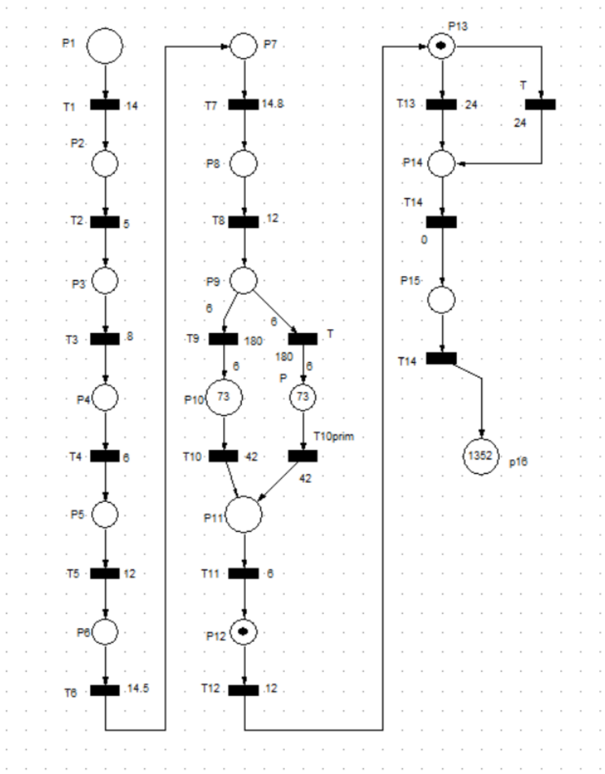

Fig. 5. Simulation variant II Petri nets

As a result of the optimisations implemented, the line recorded a significant increase in performance, reaching a total of 1,352 coils completed in an 8-hour shift. This evolution reflects the fact that supplementing resources in critical areas and reorganising the operational flow lead to a considerable reduction in bottlenecks and a major improvement in the overall throughput of the system. Variant II thus confirms the effectiveness of structural interventions and demonstrates the high potential of simulation for supporting optimisation decisions.

3.2. Modelling with Tecnomatix Plant Simulation

The effectiveness of using the Tecnomatix Plant Simulation programme has been highlighted in applications related to flow line manufacturing. The paper presents the possibility of using Tecnomatix Plant Simulation software for the functional optimisation of flow lines, specifically a coil manufacturing line. The coil manufacturing line model is created in Tecnomatix using Tecnomatix Plant Simulation software. As in the case of Petri net simulation, we will also perform two simulation variants in Tecnomatix. The first variant of the model created in the Tecnomatix programme can be seen in Fig. 6 and comprises 16 work cells made up of robots, thus the line being automated, requiring only the operation of the robot.

The first variant of the model created in the Tecnomatrix programme can be seen in Fig. 6 and comprises 16 work cells made up of robots, thus automating the line and requiring only a single operator at the first work cell. Each work cell is allocated a processing time in which to perform the operation.

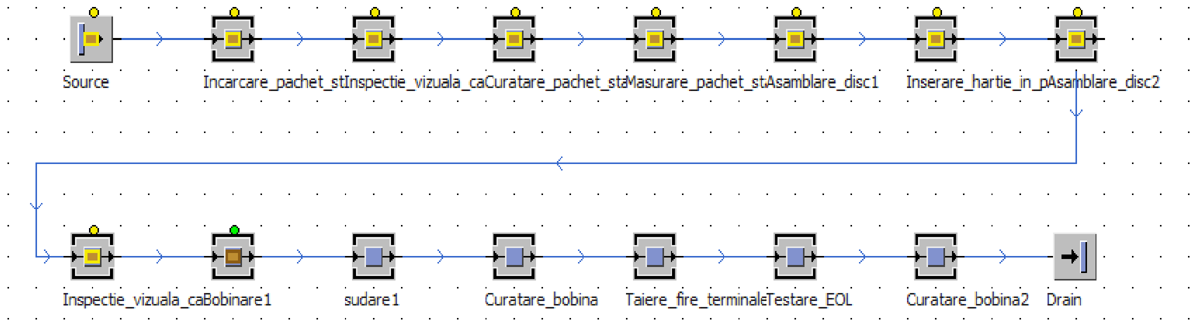

Fig. 6. Variant I of the production line in Tecnomatix

Once the simulation corresponding to an 8-hour production interval was completed, the model generated a total of 159 finished product units shown in Fig. 7, representing fully processed coils. This result reflects the effective capacity of the initial configuration of the production line and highlights the degree of limitation imposed by the technological flow and the distribution of existing resources in this variant. The value obtained confirms that, in the absence of additional structural optimisations, the line operates below its maximum potential, being influenced by individual process times and the occurrence of congestion areas in critical stages of the flow.

The second variant of the model proposes a comprehensive set of structural changes to the production line, with the aim of eliminating the bottlenecks identified in the initial configuration and significantly improving the total production capacity. Thus, in this version, the work cells related to the winding operation and those associated with the coil welding process have been doubled, an intervention aimed at reducing the excessive load on these stations and eliminating the long waiting times identified in the previous variant. By introducing additional resources on these critical segments, the production flow becomes more balanced, and the sequence of operations runs more smoothly and predictably.

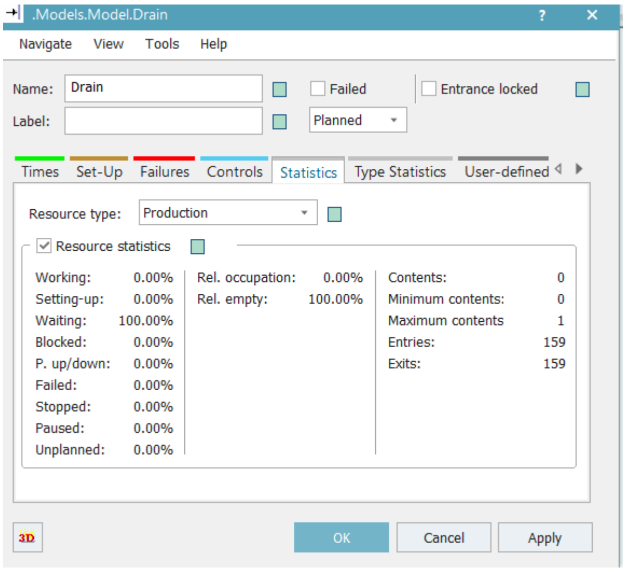

Fig. 7. Simulation result Variant I Tecnomatix

In addition to these improvements, an additional station for the EOL (End Of Line) testing operation was added in the second version. This change plays an essential role in eliminating the bottleneck previously observed at this final stage of the technological process. By operating two dedicated testing cells in parallel, the waiting time for products before final evaluation is significantly reduced, and the production volume processed during the simulation interval increases considerably.

Overall, these interventions – doubling the number of winding and welding cells and expanding EOL testing capacity – contribute to streamlining the technological flow, reducing downtime and increasing resource utilisation. The direct result is a remarkable increase in production at the end of the simulated 8 hours, highlighting the efficiency and necessity of the changes applied. The complete configuration of Variant II, including the new cells introduced and the optimised flows, is illustrated in Fig. 8.

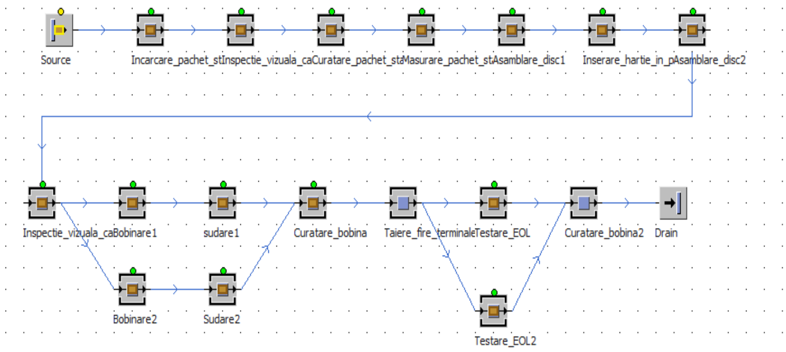

Fig. 8. Result of the Variant II simulation in Tecnomatix

As a result of the optimisations implemented, the production line recorded a significant increase in operational capacity, highlighting the cumulative impact of the changes made to the technological flow. Simulation of a complete 8-hour shift demonstrated that, in the optimised configuration, the system can produce a total of 1,430 coils, which is a notable improvement compared to the initial variant. This substantial increase in productivity reflects both the effectiveness of the bottleneck elimination measures and the improved load balancing between the different work cells.

The result confirms the relevance of the strategies adopted to decouple critical operations and increase the degree of parallelisation within the process. Through the appropriate redistribution of resources, the reduction of unproductive times and the optimisation of the sequence of operations, the production flow has become more stable, more coherent and capable of handling higher volumes without additional congestion. In addition, this development indicates that the simulated system has superior resilience to load variations and can maintain a high level of performance even under intensified operating conditions [10].

This progress is also backed up by the stats from the Tecnomatix Plant Simulation platform. In Fig. 9, you can clearly see that the total number of products coming out of the system at the end of the 8-hour simulation is 1,430 reels, which is shown in the Entries and Exits fields. This confirmation, provided directly by the simulation engine, constitutes solid empirical evidence of the optimal functioning of the line in the modified configuration and highlights the consistency between the conceptual model, the technical implementation and the numerical results obtained.

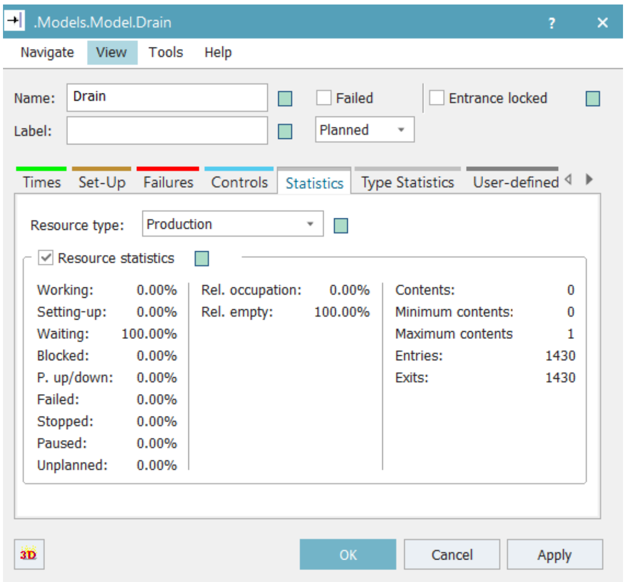

Fig. 9. Result of the simulation Variant II in Tecnomatix

Therefore, the analysis performed demonstrates not only the increased performance of the production line, but also the methodological validity of the optimisation process applied. The superior performance of the optimised model reaffirms the usefulness of digital simulation as a decision support tool in the design and modernisation of industrial systems.

4. Comparison between Petri Networks and Tecnomatix

The comparative analysis between Variant 1 and Variant 2 highlights the substantial impact that structural optimisations have on the performance of a production line modelled in both Petri Networks and Tecnomatix Plant Simulation. In Variant 1, both simulation environments provided results that reflect the initial configuration of the system, characterised by limited flow and the emergence of critical points that restricted total production. Petri nets generated a total of 82 finished products, while the simulation performed in Tecnomatix indicated a production of 159 parts. The significant difference between these results suggests that Tecnomatix benefits from a higher level of granularity in process description and has advanced flow analysis capabilities, which facilitates more accurate identification of bottlenecks and estimation of productivity closer to the behaviour of a real system.

In Variant 2, where the model was optimised by doubling the critical stations and eliminating major bottlenecks, both tools recorded spectacular increases in performance. Petri nets managed to generate 1,352 parts in an 8-hour shift, while Tecnomatix achieved 1,192 products. This reduction in the difference between the results reveals the ability of both methods to respond positively to structural optimisations, demonstrating that, under conditions of consistent and well-calibrated modelling, the differences between the two tools are blurred. At the same time, these results confirm that the potential for improvement is present in both simulation platforms, but the way each method manages parallelisation, cycle times and internal resources leads to specific variations in performance indicators.

Overall, the comparison between the two variants shows that the transition from a basic scenario to an optimised one leads to a major increase in productivity in both simulation systems, but the evolution is more pronounced in the case of Petri Networks, where the performance leap is much more visible. This finding suggests that, although Tecnomatix maintains its advantages in terms of visualisation, simulation ergonomics and bottleneck analysis, Petri Networks can offer competitive performance when the model is refined and the system structure is treated with the rigour required by their formalism.

5. Conclusions

Petri nets are a formal tool for modelling discrete event systems, widely used in the analysis of industrial processes, concurrent flows and distributed systems. Compared to commercial software tools, this formalism offers a number of conceptual advantages that make it extremely valuable in the design and logical verification stage of a production line. A first major advantage is the clarity and precision in representing concurrency. Unlike other modelling methods, Petri nets allow an explicit visualization of the processes that can occur simultaneously and how resources are distributed in the system. This capability is essential in the analysis of complex production lines, where overlapping operations, conflicts, and synchronization of process elements can decisively influence overall performance.

A second advantage is the possibility of formal analysis of system behaviour. Petri nets allow the verification of fundamental properties such as safeness, boundedness and, above all, liveness, a property that guarantees that the system cannot reach a deadlock state. The importance of liveness is remarkable:it prevents deadlocks, it ensures reliability in system operation, it contributes to a continuous and uninterrupted flow of production.

In addition, Petri nets offer conceptual flexibility, being easy to extend to capture additional characteristics of the process. There are variants such as Timed, Coloured or Stochastic Petri Nets, which allow the introduction of process times, probabilities or different types of resources, increasing the realism of the model and the possibility of analysing complex situations.

However, Petri nets also have significant limitations. First, in the context of a real industrial system, they can become difficult to manage on a large scale. As the number of transitions and positions increases, the model becomes difficult to follow and manipulate, requiring an advanced level of theoretical expertise to correctly interpret the results.

Another disadvantage is related to practical performance in simulation. The results obtained in this study indicate that Petri nets had systematically lower productivity than Tecnomatix Plant Simulation in all modelled variants. This difference can be explained by the limitations of Petri Net software tools, which do not have advanced optimisation, visual analysis or dynamic flow management mechanisms, elements that are present in modern industrial platforms.

Tecnomatix Plant Simulation is an advanced tool developed for the analysis, optimisation and simulation of manufacturing lines, integrating both the logical and visual-dynamic components of industrial processes. The main advantage of Tecnomatix is its superior performance in generating results, as demonstrated by all the variants simulated in the study. The platform features algorithms for optimisation and intelligent flow management, which allow for the automatic identification of bottlenecks and underutilisation of resources. Another essential element is the advanced visualisation capability. 2D and 3D simulations enable real-time monitoring of flows, the occupancy rate of each cell and transient states, providing a clear picture of how the elements of the line interact. This level of detail is extremely valuable to engineers, facilitating immediate understanding of problems and rapid identification of solutions.

The platform also has the advantage of excellent integration into the Siemens ecosystem, allowing models to be connected to CAD design tools, MES systems, or logistics simulation modules. Thus, Tecnomatix can function as a complete digital simulation solution for modern industry. Although very powerful, Tecnomatix also has some disadvantages. The first is the high cost of the licence, which can be a barrier for small businesses or academic institutions with limited budgets. In addition, the platform requires advanced technical knowledge, with a substantial learning curve required to use the modelling tools and simulation analysis effectively.

Looking at the overall pros and cons of the two methods, we can say that Tecnomatix Plant Simulation is the best option for simulating and optimising real industrial flows because of its high performance, advanced visual modelling capabilities, and specialised tools for identifying bottlenecks.

In contrast, Petri nets remain a fundamental tool for formal and logical analysis of systems, being extremely useful in the conceptual stage for verifying the behaviour and theoretical properties of the process.

Therefore, the choice between the two methods depends directly on the purpose of the simulation. When the objective is formal analysis, logical verification of system behaviour and theoretical studies, Petri nets are the most suitable option. On the other hand, when the goal is to obtain a realistic industrial simulation, focused on operational optimisation, performance evaluation and detailed visualisation of production flows, the appropriate method is Tecnomatix Plant Simulation.

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