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THE USE OF HIERARCHICAL MODELS WITH COLORED PETRI NETS IN THE STUDY OF ROBOTIC MANUFACTURING PERFORMANCE

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Abstract: This paper is a study through which robotic manufacturing cells can be modeled using hierarchical Petri nets. They are an efficient tool due to their ability to model dynamic processes. The subject addressed in the paper is that of modeling and improving the manufacturing workflow for the pipe bending process. Within the research carried out, three models are compared with Petri nets made in the CPN IDE program with the aim of improving the system. The first model represents the initial production flow. The second model improves the sequence of robot movements by introducing additional tasks to the robot serving the production process. The third model introduces a double clamping system, allowing the simultaneous manipulation of two pipes, which leads to a significant increase in productivity. The streamlining of the workflow and improvement of resource use are confirmed by the simulation results.

Keywords: Petri nets, hierarchical modeling, industrial robotics, flexible manufacturing systems.

1. INTRODUCTION

By using Petri nets, we can model, simulate and analyze the behavior of these systems, highlighting bottlenecks or sensitive areas in the production workflow, and thus improve processes for greater efficiency.

Current modeling and simulation tools, such as CPN IDE, allow modeling, simulation and analysis of Petri nets, allowing the development of various applications in various industrial fields. These tools are used to evaluate the performance of production systems and waiting times, to simulate the behavior of production systems subjected to various limit situations and to identify situations with possible bottlenecks.

This paper addresses aspects of modeling and simulation of a robotic production system, using hierarchical Petri nets. The manufacturing system consists of a robotic cell composed of a series of hardware and software components with the ultimate goal of processing pipes. The goal is to reduce errors and improve production efficiency.

The paper [1] presents a methodology for designing material flow for flexible manufacturing systems in order to establish the

optimal architecture of the analyzed system. The research provides a solution for modeling and improving material flows in advanced production systems. By using a dedicated analysis and simulation software, the system structure can be established, and specific technical and economic parameters can be determined for each processing and transport capacity.

The Petri net model of a flexible assembly cell is presented in [2]. The cell is composed of a handling robot, a computer vision system and a transfer system. The cell is used to assemble several products. Only two of them are present in the paper.

The paper [3] presents how transition-timed Petri nets can be used to model and simulate a robotic manufacturing cell. In a transition-timed Petri net a value time is associated to transitions of Petri Nets and it represents the time required for firing a transition. A welded subassembly composed of three types of parts is made within the cell. The cell has two welding robots and a handling robot. works inside the cell. Several variants of Petri net models have been developed. The third variant, the closest to the real system, considers elementary sequences

performed by the cell components, including those supplying the welding parts.

Paper [4] proposes a stochastic Petri net model to verify and analyze the performance of a flexible manufacturing system. The validation of the proposed model was carried out with MATLAB simulation through a specific FMS case study. The model evaluates the time that a part spends in different stages of the manufacturing process.

Paper [5] develops a deadlock prevention strategy for a system modeled with Petri nets, by defining appropriate time constraints associated with certain transitions. Thus, a scheduling of transition execution priorities is performed, in such a way that transition sequences that lead to deadlocks are avoided. Examples are provided to demonstrate the effectiveness of the presented methodology.

The hierarchical model with colored Petri nets of a flexible carousel manufacturing system is presented in [6]. The system is composed, in turn, of seven cells: five processing cells and two assembly cells. Each cell is serviced by a robot. The cells are connected by a carousel-type transfer system. Through modeling and simulation with colored Petri nets, the system's performance is analyzed in terms of input flows and the manufacturing cycle. The model considers various input factors, such as: average processing time, average loading/unloading time, average assembly time, buffer capacity, average repair time of production resources.

The use of modeling and simulation with timed colored Petri nets arose from the need to evaluate some variants of robotic manufacturing cells [7]. The models were designed considering structural and functional improvement solutions. The respective solutions materialize in two cell variants. The two variants were also modeled, the existing variant was also modeled. Through simulation, the results that will be obtained in the case of the two new variants, in relation to the existing variant, were highlighted.

After identifying the cell variant to obtain the highest pipe production, the costs necessary to materialize the proposed solution were also evaluated. The economic calculations performed highlighted the fact that the investment can be amortized in a reasonable time frame.

2. DESCRIPTION OF THE ROBOTIC MANUFACTURING SYSTEM

The distances in the engine compartment of cars are not large, but the pipes that ensure the circulation of various fluids cannot be designed in a straight line. They must avoid various components and ensure direct connections with flexible hoses at the end. Thus, the two needs arise: to bend the pipes and to modify the shape of the ends to make the connections.

Figure 1 shows the manufacturing workflow for obtaining a bent pipe with formed ends.

To carry out these processes, it is necessary to have an automated system that includes the following hardware components:

- Smart pipe bending machine together with the necessary bending tools;
- Yaskawa handling robot together with the pipe handling device;
- Warehouse for storing pipes;
- Machines for forming pipe ends;
- Chute and container, respectively inclined bar for the evacuation of pipes by the robot;
- Pneumatic pistons, sensors, linear guides;
- Protective fences with doors.

The software component consists of automation equipment, robot programs and bending machine programs.

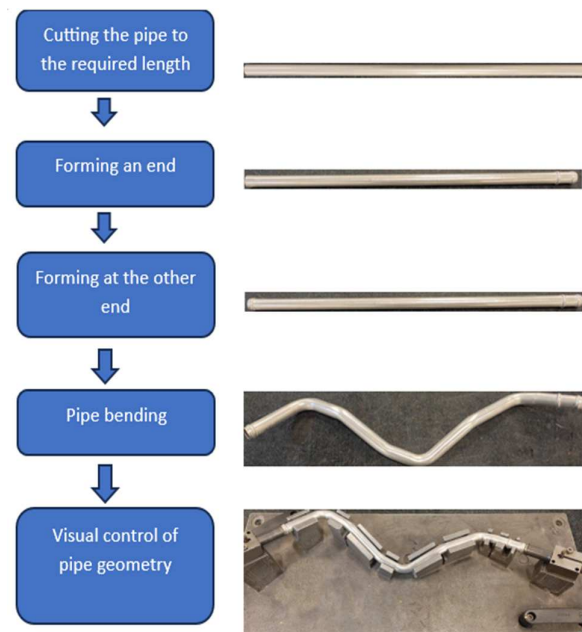


Fig. 1. Steps required to produce a bent pipe with formed ends.

By using a model based on Petri nets, the paper explores the possibility of simulating and analyzing the behaviors of this automated manufacturing system, highlighting the interactions between individual processes, improving workflows and identifying possible collisions or blockages during operations. The main objective of the paper is to propose a simulation method that supports performance improvement and production cost reduction within the described automated system. The layout of the manufacturing system is presented in figure 2.

In the current situation, the workflow in the manufacturing cell is sequential, the robot can only handle one pipe at a time:

- the robot positions itself at the pipe magazine and grips the pipe prepared for processing;
- the robot transfers the pipe to the forming machine 1;
- the first pipe end is formed;
- the robot transfers the pipe to the intermediate clamp;
- the robot changes the clamping position;
- the robot transfers the pipe to the forming machine 2;
- the second pipe end is formed;

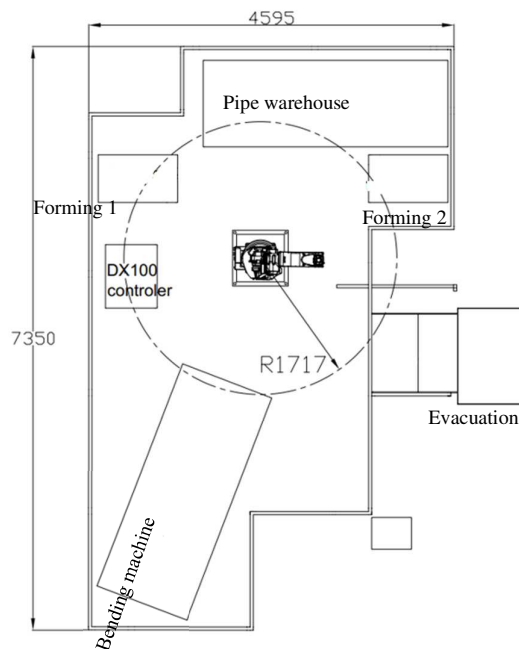


Fig. 2. Manufacturing system layout.

- the robot transfers the pipe to the bending machine;
- the pipe is bent;
- the robot grips the bent pipe and takes it to the evacuation area.

3. PETRI NETS MODELING OF THE MANUFACTURING CELL

3.1 Petri nets model – version 1

Figure 4 shows the Petri net model of the manufacturing cell in its initial state. The execution of a transition (action) is conditioned by the place that precedes it. The meanings of the places and transitions are presented in Table 1.

Table 1

Places and transitions used in the Petri net model.

No	Sym	Explanation	Time
1	P1	Pipe warehouse	$m_0(P1) = 700$
2	T1	Pipe lifting	$d_1 = 4 \text{ sec}$
3	P2	The pipe is in the position to be picked up by the robot	$m_0(P2) = 0$
4	P17	Pipe detection sensor	$m_0(P17) = 1$
5	T2	The robot grasps the pipe	$d_2 = 1 \text{ sec}$
6	P3	The robot has the pipe.	$m_0(P3) = 0$
			
28	P14	The robot has the pipe.	$m_0(P14)=0$
29	T14	The robot transfers the pipe to the discharge area	$d_{14} = 7 \text{ sec}$
30	P15	The robot is at the evacuation area, the pipe is in the container	$m_0(P15)=0$
31	T15	The robot positions itself at the charger.	$d_{15} = 7 \text{ sec}$
32	P16	The robot is on the loader.	$m_0(P16)=1$
33	P18	Pipe counter	$m_0(P18)=0$

Running the simulation for an eight-hour shift results in an expected production of 334 pipes. This detail can be seen in Figure 3, which reflects the state of the model after 28.800 seconds of running.

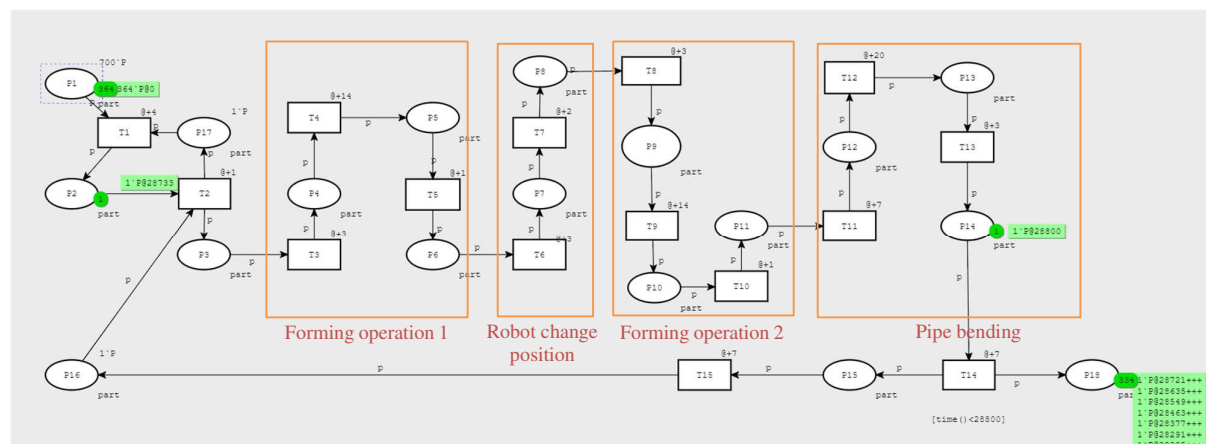


Fig. 3. The Petri nets model.

3.2 Petri nets model – version 2

To improve the analysis and clarity of the model, it was decided to create an initial Petri net model using hierarchical Petri nets. This method allows the model to be divided into smaller components, organized on hierarchical levels, thus facilitating both the understanding and verification of the system's properties.

Rebuilding the model involved breaking down the initial model into several submodels, creating a base model that coordinates the submodels through input-output transitions. Maintaining the correctness of the initial

behavior by ensuring that constraints and relationships between components are respected.

Through this approach, a modular model was obtained, easier to analyze (Fig. 4).

In the “Forming 1” submodel, the robot picks up the pipe and transfers it to forming station 1 (transition T1, Fig. 5). The pipe is prepared for the machining process (transition T2, Fig. 5). After the machining is completed, the robot picks up the pipe again, ensuring that it is handled properly for the next step in the process.

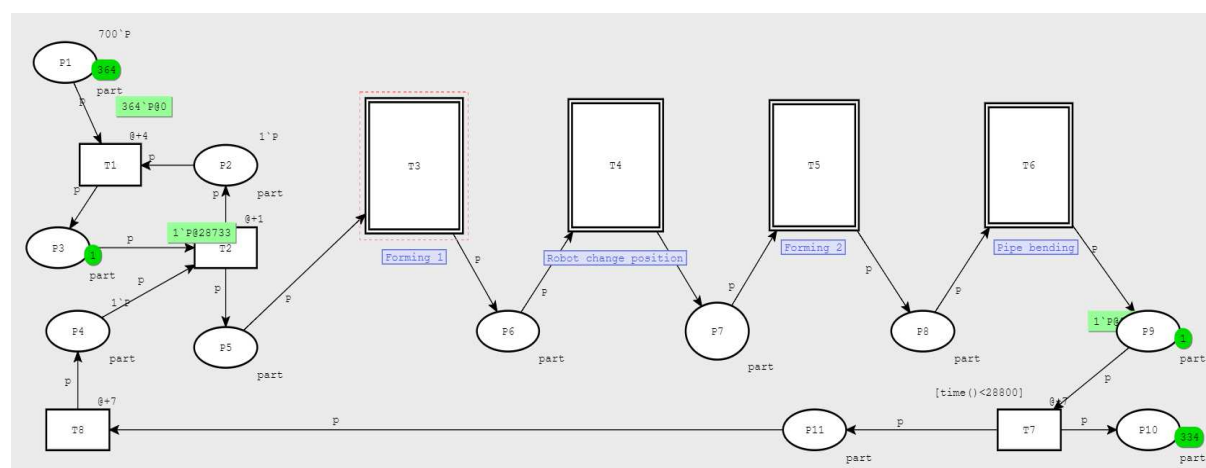


Fig. 4 The hierarchical Petri nets model.

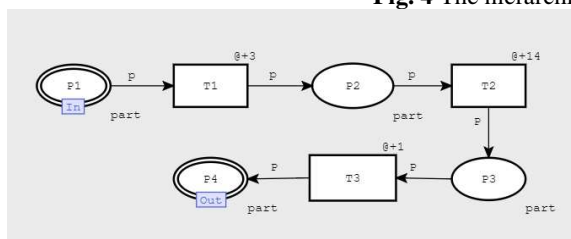


Fig. 5. Submodel “Forming 1”.

The robot moves the pipe to an intermediate position, where it is temporarily placed before the next step (transition T1, Fig. 6). The robot then adjusts its gripping position to ensure optimal handling. After this adjustment, the robot has the pipe and is ready for the next step in the process.

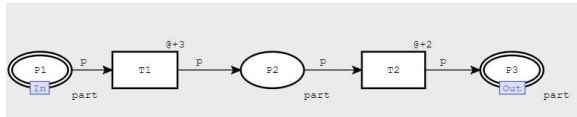


Fig. 6. The "Robot change position" submodel.

The “Forming 2” operation is similar to the first stage with different processing and handling times. The robot picks up the pipe and fixes it for handling. Then, it transfers it to the bending machine, where it is processed according to specifications (transition T1, Fig. 7).

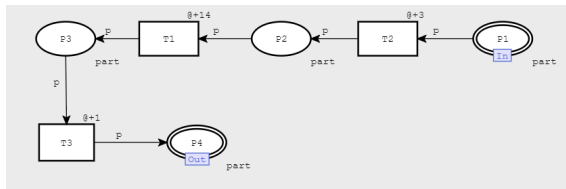


Fig. 7. The “Forming 2” submodel.

After the bend is completed, the pipe remains in the processing position until the robot picks it

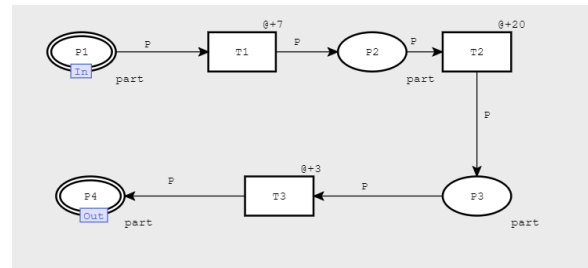
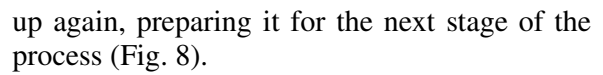


Fig. 8. The “Bending Pipe” submodel.

To reduce this waiting time and increase productivity, the order of execution of the robot movements can be changed so that during pipe bending the robot transfers a pipe from the loader to formation 1. In this case we will have two pipes per workflow, one at “forming 1” steps and one bending operation.

To simulate this production workflow, a new Petri net model was created, shown in Figure 9.

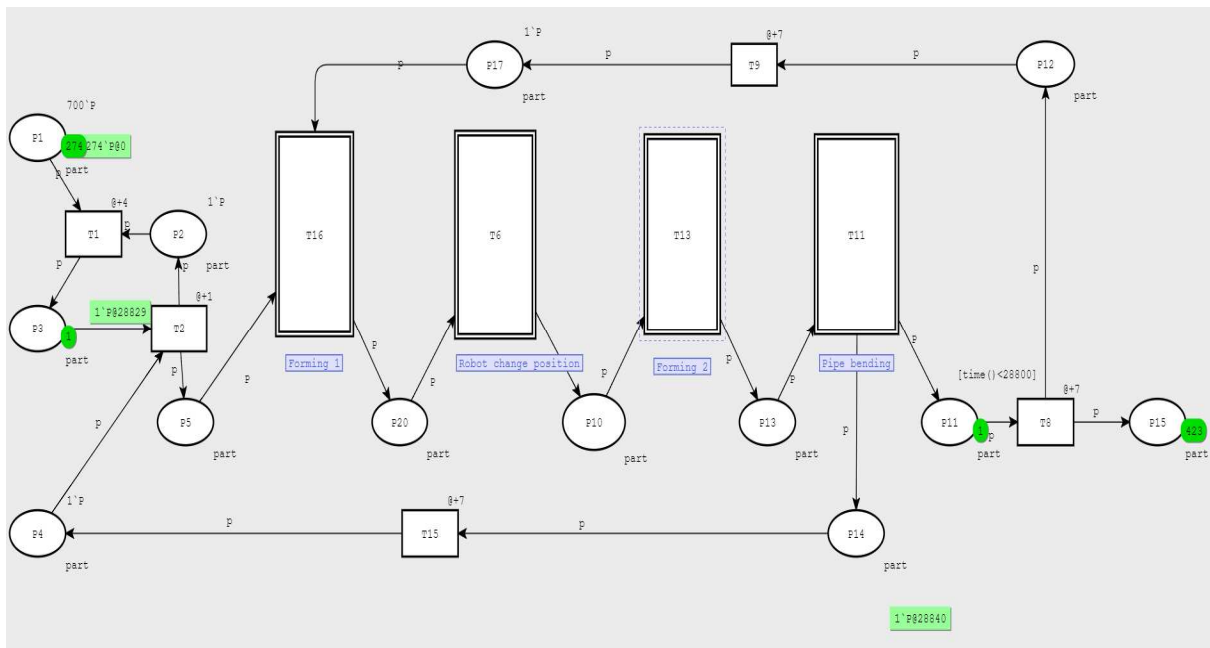


Fig. 9. Petri net model in version 2

Running the simulation for an eight-hour shift results in production of 423 pipes. This can be seen in Figure 9, which reflects the state of the net after 28,800 seconds of running.

The production obtained with this model is 89 parts higher than the previous model, which means an increase of 26.64%.

3.3. Petri nets model – version 3

In modern manufacturing processes, reducing manufacturing times is a crucial objective for increasing efficiency. One such improvement, shown in Figure 10, was achieved by introducing a new end effector to the robot, allowing the simultaneous handling of two

pipes. This modification brings a significant advantage in the management of the production workflow, allowing two pipes to be handled simultaneously in different areas of the process.

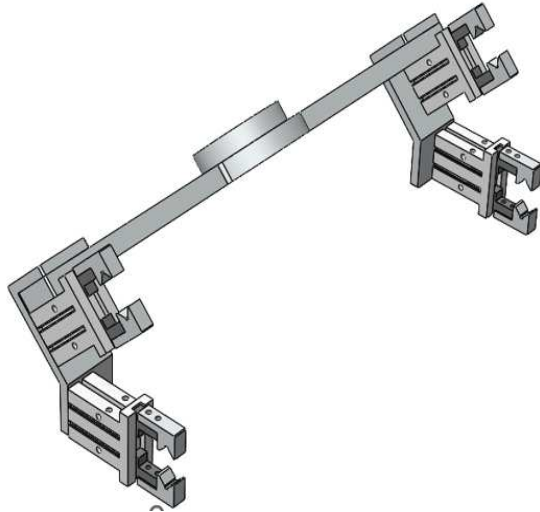


Fig. 10. Pneumatic gripper with two gripping positions.

Although the structure of the machines and their positioning do not change, the new system offers the possibility of handling two pipes in two distinct scenarios. The first case involves the handling of two straight pipes, in the area of the forming machines, which allows the improvement of the initial stage of processing. The second case involves the handling of a straight pipe and an already bent one, in the area of the bending machine, thus facilitating the transition between the forming and bending processes.

In modeling the manufacturing system we will use the same hierarchical model, the modifications will be made only at the level of the submodels that define the stages of the manufacturing system.

This improvement results in a reorganization of the manufacturing workflow, allowing multiple pipes to be processed simultaneously. Thus, the robot starts by taking a formed pipe (A) from the first forming machine (Fig. 11) and, at the same time, picks up a pipe ready for processing (B) from the pipe magazine. After transferring pipe B to forming machine 1, the

robot transports pipe A to the intermediate clamp (Fig. 12), where it remains temporarily while the first end of pipe B is formed. This is followed by changing the clamping position and taking a new formed pipe (C) from forming machine 2. The robot continues the process, placing pipe A in forming machine 2, while pipe C is moved to the bending machine. During this time, the forming of the second end of pipe A takes place (Fig. 13).

After the bending operation is completed, the robot unloads the bent pipe (D) and loads pipe C into the bending machine so that the process continues without interruption. While the bending of pipe C begins (Fig. 13), the robot transfers the bent pipe D to the discharge area, thus preparing the ground for the resumption of the manufacturing cycle by returning to the first stage of the process.

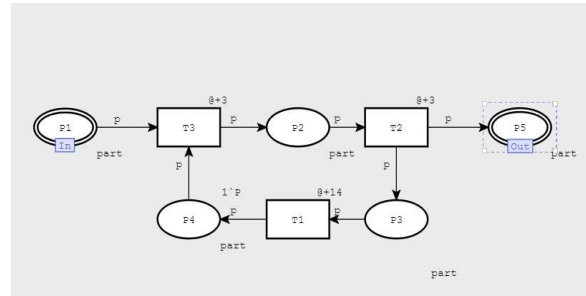


Fig. 11. "Forming 1" submodel.

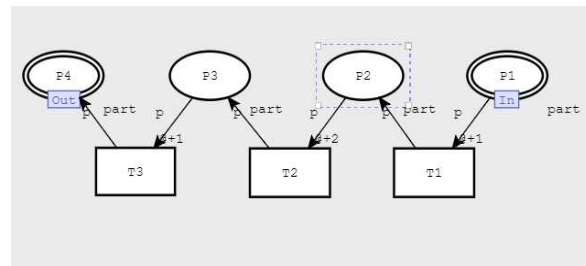


Fig. 12. The "Robot change position" submodel.

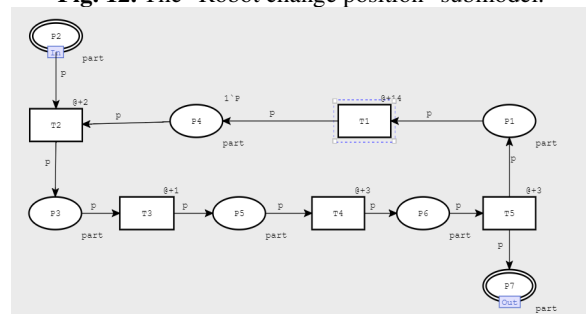


Fig. 13. The "Forming 2" submodel.

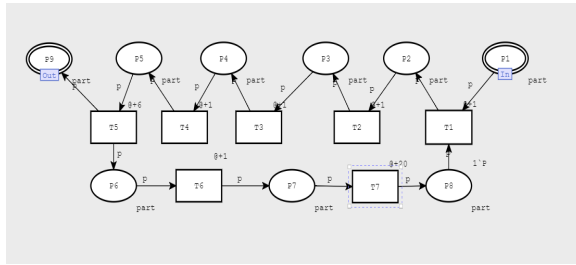


Fig. 14. The “Pipe Bending” submodel.

Through this strategy, the production workflow is improved, allowing the simultaneous processing of four pipes at different stages of the process. The introduction of a dual handling system not only improves production efficiency, but also contributes to reducing processing time, improving resources and increasing the overall productivity of the system.

Running the simulation for an eight-hour shift resulted in a predicted production of 700 pipes.

This result is with 366 pipes higher than the simulation result of the first model, and 277 pipes higher than the second model. This means an increase in production of 109% and 65.48% respectively from one case to the other. To implement the technical solution with the robot equipped with the special gripping device, the necessary costs were calculated, resulting in 4443 euros. Under these conditions, considering the increase in production volume, from 334 pipes/shift to 423 pipes per shift, the amortization of the investment can be achieved in 22 working days.

4. CONCLUSION

The paper highlights the importance of using Petri nets in modeling and simulating a pipe manufacturing system. Three production workflow variants were analyzed. Each variant brought successive improvements in the productivity of the system.

Compared to other production system modeling tools such as Markos chains or AI-based scheduling methods, this method is appropriate for the modeled system, considering its structural and functional characteristics. The modular or hierarchical nature of the model allows for punctual intervention in submodels of

the generated model when necessary. At the same time, we have the possibility of detailed graphical modeling, which makes it easier to apply.

The first model variant presented the initial production workflow, in which the robot handled a single pipe at a time. The simulation of this model generated a production of 334 pipes in eight hours of operation.

The second variant brought an increase in production by modifying the order of the robot's movements, so that, during the bending operation, it would prepare and transfer another pipe for forming. Thus, production was increased to 423 pipes, representing an improvement of 26.64% compared to the first variant.

The third variant introduced a new end effector. This production workflow variant allows the simultaneous manipulation of two pipes. This allows several operations to be carried out in parallel. This improvement led to an increase in productivity of 700 pipes produced in an eight-hour work interval, which represents an increase of 109% compared to the first variant.

Comparing the three models and implicitly the results obtained, it is confirmed that the use of Petri nets is an efficient method of analyzing production workflows. This leads to improved manufacturing system performance. Thus, this approach offers an efficient method of analysis and improvement for industries that use robotic processes, contributing to reducing processing time and increasing operational efficiency.

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Utilizarea modelelor ierarhizate cu rețele Petri colorate în studiul performanțelor celulelor de fabricație robotizate

Această lucrare este un studiu prin care pot fi modelate celule de fabricație robotizate cu ajutorul rețelelor Petri ierarhizate. Acestea sunt un instrument eficient datorită capacității lor de a modela procesele dinamice. Subiectul abordat în lucrare este cel al modelării și îmbunătățirii fluxului de fabricație pentru procesul de îndoire a țevelor. În cadrul cercetării realizate sunt comparate trei modele cu rețele Petri realizate în programul CPN IDE cu scopul îmbunătățirii sistemului. Primul model reprezintă fluxul de producție inițial. Al doilea model îmbunătățește secvența mișcărilor robotului, prin introducerea unor sarcini suplimentare robotului care deservește procesul de producție. Al treilea model introduce un sistem de prindere dublă, permițând manipularea simultană a două țevi, ceea ce duce la o creștere semnificativă a productivității. Eficientizarea fluxului de lucru și îmbunătățirea utilizării resurselor sunt confirmate de rezultatele simulării.

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