ORIGINAL PAPER

PETRI NET MODELING OF A PRODUCTION SYSTEM WITH PARALLEL MANUFACTURING PROCESSES

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Abstract. *This paper presents the modelling and control of a flexible manufacturing system with integrated Industry 4.0 concepts using Petri nets. The flexible manufacturing system is composed of 7 workstations that ensure the assembly and disassembly of two types of products on two parallel production processes. The two parallel processes, in-line and in-cell production processes, ensure the assembly of the products and disassembly of the defects with a minimal number of stations. wo types of controls, local and centralized, are implemented in the control of production processes. The local control, based on the PLCs of each station, ensures the control of the assembly process at the workstation level. The centralized control ensures the obtaining of desired results at the level of interaction between the stations and also the implementation of the optimization algorithm results. To better understand and develop the control of the system a Petri net model was developed. Based on the properties of the Petri nets was possible to simulate and verify the assembly process and data flow inside the flexible manufacturing system. The developed model also ensures no bottlenecks at the data transmission and processing of the production information from the client to the production hardware.*

Keywords: *Petri net; flexible manufacturing system; Industry 4.0.*

1. INTRODUCTION

In the current manufacturing environment, the flexible manufacturing capabilities represent a necessity, given the constant changes in the demand for different products [1]. If some years ago the production was centred on a small number of variations of different products, today the number of variations of a product is many times bigger and directly related to the final client demand [2]. In compensation to the mass production concepts, today, the manufacturing of a product is done based on the configuration requirements made by the client [3], with the mass production of the necessary components.

This request-based production determines a high degree of complexity in the manufacturing systems [4]. This manufacturing systems need to have a high degree of flexibility. The degree of flexibility increases with the necessity of having a lower number of equipment involved in the production process and use of the equipment in an optimal manner

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[5, 6]. To ensure the use of a minimal number of stations some products need to travel between several workstations not necessarily in a linear manned [7]. This results in different manufacturing concepts being implemented in a single manufacturing system [8]. Beside the in-cell and in-line production concepts as multi-agent paradigm can be implemented in the new production systems [9]. Another concept is represented by reconfigurable manufacturing systems including both physical reconfigurations, which involve hard changes to equipment and machine arrangement, and logical reconfigurations, which involve soft changes like re-routing and re-planning [10].

But usually implementing some of the new flexible manufacturing concepts require a complete design and replacement of existing manufacturing equipment [11]. But as in most cases a complete replacement of the existing manufacturing systems is not possible, so a redesign of this systems is necessary [12]. The usual manufacturing system is composed of several workstations interconnected by a conveyor ensuring a linear production process [13], [14]. To redesign a linear manufacturing system to a flexible one is necessary to ensure the reachability of each workstation from every point of the manufacturing system [15]. This is ensured by a transportation system parallel with the manufacturing line [16]. Using the transportation system, an optimal number of workstations can be implemented eliminating most of the repetitive workstations [17].

Beside the hardware redesign an information processing and transmission design is necessary. In implementing most of the Industry 4.0 concepts a data transmission and processing is necessary as a base for technologies as collaborative robots or augmented reality [18, 19]. One of the most important data transmission and processing is represented by the transmission of data vertically between factory layers [20, 21]. This kind of data transmission can provide a better production data communication directly from the client to the manufacturing system [22, 23].

Existing conventional modelling methods such Petri nets [24, 25] can be used to model this flexible assembly processes and data transmission. These methods can also be used to model flexible manufacturing systems with Industry 4.0 concepts implemented and simulating the availability of these systems [26]. Petri nets have unique advantages and are more suitable than other methods for modelling production systems with Industry 4.0 architecture [27]. Petri nets are mainly used to graphically model discrete-state systems [28, 29]. Since their introduction, they have been continuously improved and are increasingly being used to realistically model production systems. In order to be able to model modern production systems, which also involve continuous states, improved variants of Petri nets can be used, such as Hybrid Petri Nets (HPN) and Timed Petri Nets (TPN) [30, 31].

This article presents the modelling, simulation and control of a flexible manufacturing system using a special variant of TPN, a Synchronized Timed Peri Nets (STPN). This enables to better represent the transmission of information between certain workstations and model or simulate parts of the flexible manufacturing system independently.

The paper is structured as follows: Section 2 presents the flexible manufacturing system from the hardware and process perspective, Section 3 will present the models and simulations developed for the flexible manufacturing system and for the data acquisition from the client. Section 4 will present the conclusion of modelling a flexible manufacturing system using the Petri nets.

2. FLEXIBLE MANUFACTURING SYSTEM

The manufacturing system considered in this paper is a flexible manufacturing system from a production point of view. The system can be used to produce a multitude of multi-layer products without the need of hardware reconfiguration. In this paper we'll be presenting only the production of two types of products, a multi-layered product, named Type 1, and a single layer product, named Type 2. The presented types of products have their personalized configurations received directly from the client trough a special interface and run through a production optimisation algorithm on a local or cloud server. Based on the optimisation algorithm results the manufacturing system receives a production sequence that ensures the manufacturing of a maximal number of products in the shortest time possible.

2.1. FLEXIBLE MANUFACTURING SYSTEM HARDWARE DESCRIPTION

The current study focuses on the manufacturing process of two distinct types of products on a Flexible Manufacturing System (FMS) which share similar construction features and components. The products are categorized based on the number of internal component layers, where Type 1 consists of multiple internal layers, and Type 2 is comprised of a single internal layer.

The FMS system considered in this study is presented in Figure 2 and comprises seven individual workstations, each performing specific tasks in the manufacturing process. Every workstation is controlled by a Programmable Logic Controller (PLC), allowing for decentralized control. Decentralized control offers a shorter response time, making it easier to integrate new equipment in the manufacturing process.

To facilitate fast communication between the PLCs, as well as between the PLCs and a local server, a Profinet communication line is employed. The local server is responsible for transmitting the necessary manufacturing sequence obtained via an optimization algorithm to the FMS. The use of a local server in this context ensures that the FMS receives the most effective manufacturing sequence, which maximizes production output while minimizing manufacturing time.

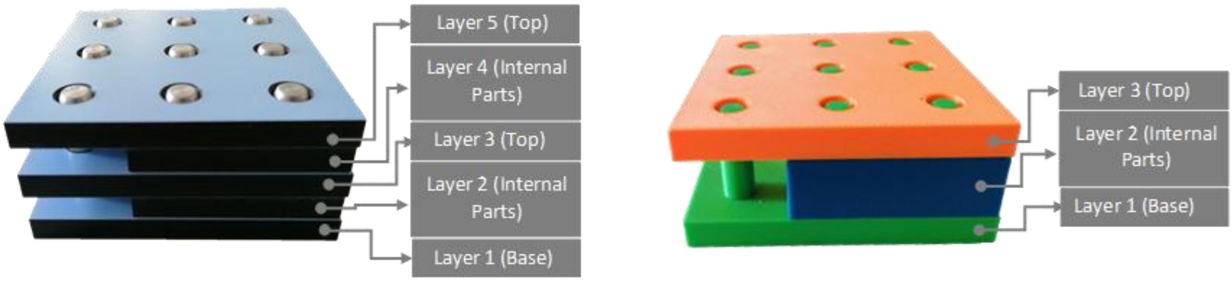

Figure 1. FMS products: Type 1 (left) and Type 2 (right).

The FMS features two robotic manipulators that are located in separate stations, one of which performs operations on the in-line section of the FMS, i.e., the flow flexible manufacturing (FFM) area, where both Type 1 and Type 2 products are manufactured. Type 2 products, with a single internal parts layer, are assembled at the four stations of the FFM, with each station dedicated to a specific operation. The robotic arm at Station 4 of the FFM is responsible for placing the internal parts in accordance with customized arrangements based on the client's requirements, allowing for a certain degree of product personalization.

For the production of Type 1 products, which comprise multiple layers and smaller internal parts, a specialized transportation system is required within the FFM, as some assembly operations need to be repeated. The FMS employs the SCARA robotic transportation system (SRTS), which comprises a SCARA robot mounted on a linear transportation device. The SRTS retrieves partially assembled products from designated positions and relocates them to previous stations, minimizing the use of equipment in the assembly process. The SRTS is connected to the PLCs within the Profinet local network, ensuring rapid information transmission.

The FMS also features a second robotic arm located at Station 3, which can participate in the assembly process on the FFM or conduct an in-cell assembly, enabling a flexible manufacturing cell (FMC) production that runs parallel to the FFM. However, since all operations are conducted in a single cell, the production rate of the FMC is slightly lower than that of the FFM. Nonetheless, the cell configuration provides greater production flexibility, as it can accommodate a wider range of products. Following assembly in the FMC, the product is retrieved by the SRTS and placed at the entry of the quality test area on the FFM, where it undergoes processing and storage if deemed acceptable.

Figure 2. Hardware structure of the flexible manufacturing system.

2.2. FLEXIBLE MANUFACTURING SYSTEM PRODUCTION PROCESS

The flexible manufacturing system (FMS) has the advantage of enabling the production of a wide variety of products while utilizing a minimal number of workstations. In addition to the products being considered, each internal parts layer of the products can be personalized based on configuration received from the client, thereby ensuring a high degree of personalization for each product. While both types of products discussed in this paper can be manufactured on the flow flexible manufacturing (FFM), only the Type 1 product is considered for production on the flexible manufacturing cell (FMC). These production assumptions are depicted in the flow diagram presented in Figure 3. Specifically, Figure 3a illustrates the production flow and interaction of these flows for the manufacturing of Type 1 on FMC and Type 2 on FFM, with the two production flows working in parallel until the quality control point where they synchronize so that the FMC product enters the FFM production flow.

In the case of the manufacturing of Type 1 product on the FFM, as depicted in Figure 3b, the partially assembled product is returned from the exit of Station 5 to the entry of Station 4 for a new set of assembly operations. However, at the point of placing the Type 1 returned product to Station 4, the product at the exit of Station 3 will have to wait for the duration of Station 4 assembly. Moreover, at the exit of Station 5, given the return of the Type 1 product, the optimization algorithm attempts to synchronize the FMC and FFM production flows such that a Type 1 product from FMC will arrive at the placing point before the quality control area, coinciding with the arrival of the Type 1 FFM product at the picking point.

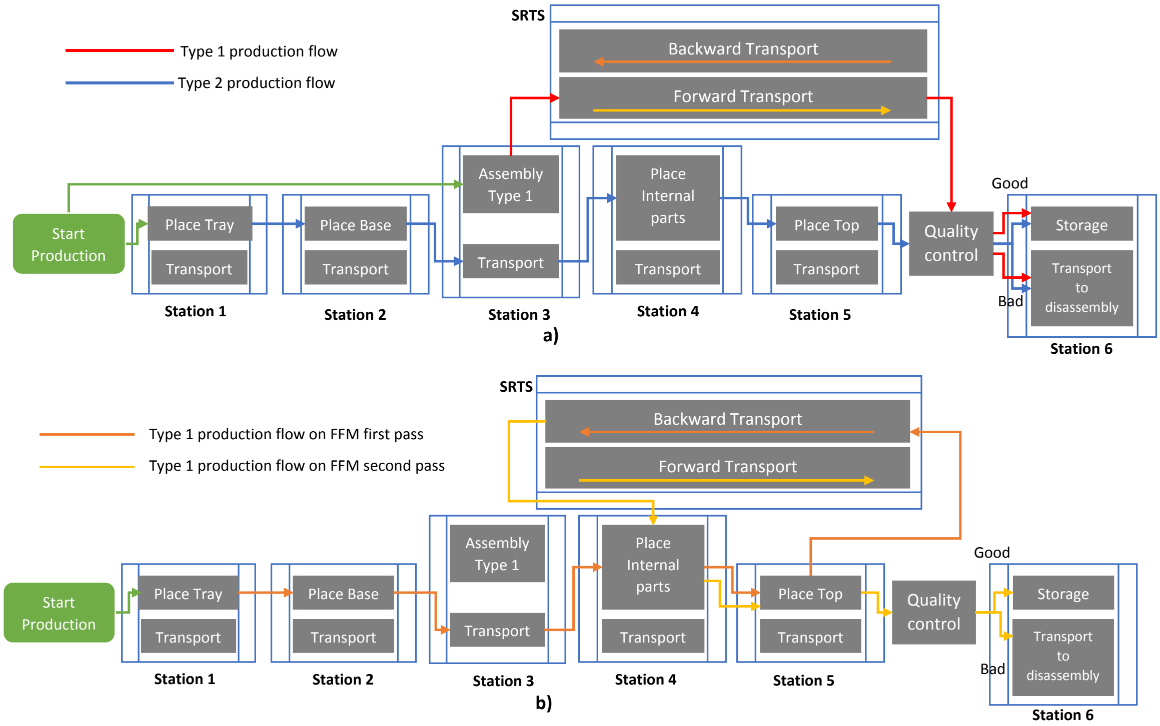

Figure 3.Task diagram: a) production flow for FMC Type 1 and FFM Type 2 manufacturing, b) production flow for FFM Type 1 manufacturing.

3. SYSTEM MODELING AND SIMULATION USING PETRI NETS

To better understand the production system and to ensure that the FMS works without bottlenecks a modelling and simulation of the system is necessary. Given the event-based control of the system, the know production duration and the synchronisations between certain productions flows the Synchronized Timed Petri Nets (STPN) can be used.

Using STPN we can model and verify the FMS production flow but also the process of data acquisition and processing for obtaining the manufacturing sequence. For the FMS the model will be formed from different sections representing the FFM production process, FMC production process and the data transmission modelling for both types of products.

3.1. INDUSTRY 4.0 INTEGRATED FLEXIBLE MANUFACTURING SYSTEM MODEL

In the case of the FMS, the Petry net model can be represented trough a STPN (Fig. 4) expressed as:

$$SPN_{FMS} = \langle TPN_{FMS},\ \mathrm{E}_{FMS},\ \mathrm{Sync}_{FMS} \rangle$$

with the timed Petri net:

$$TPN_{FMS} = \langle P_{FMS},\ \mathrm{T}_{FMS},\ \mathrm{I}_{FMS},\ \mathrm{O}_{FMS},\ m_{0\_FMS},\ \mathrm{temp}_{FMS} \rangle$$

having the places set space defined by

$$P_{FMS} = \{ P_{lasmb},\ P_{casmb},\ P_{dataT1},\ P_{dataT2}, P_{ctrFMS} \}$$

where:

$P_{lasmb} = \{P_i\}_{i=\overline{1,21}}$ represents the set of places modelling the FFM production flow for both Type 1 and Type 2 products, in the case of Type 1 production flow is also included the transportation of the product from the exit of Station 5 to the entry of Station 4.

$P_{casmb} = \{P_j\}_{j=\overline{22,29}}$ representing the set of places associated to the production flow of the FMC, this includes the manufacturing operation in the Station 3 cell but also the transportation of the product from FMC to the entry of Station 6, at the quality control point.

$P_{dataT1} = \{P_k\}_{k=\overline{30,39}}$ representing the discrete places associated with the representation of the data flow of the Type 1 product parallel with the production flow and interacting with it.

$P_{dataT2} = \{P_k\}_{k=\overline{40,51}}$ representing the discrete places associated with the representation of the data flow of the Type 2 product parallel with the production flow, including the returning of the product to Station 4 and with it the return of the product information to Station 4 also.

$P_{ctrFMS} = \{P_c\}_{c=\overline{51,64}}$ representing the discrete places associated to the control functions related to a decision action on the assembly flux or the information flux and also coordinating the two fluxes.

The transitions set space of the Petri net is represented by

$$T_{FMS} = \{ T_{lasmb},\ T_{casmb},\ T_{dataT1},\ T_{dataT2} \}$$

where:

$T_{lasmb} = \{T_i\}_{i=\overline{1,19}}$ representing the set of discrete transitions related to the production flow on the FFM, including the transport of Type 1 products from the exit of Station 5 to the entry of Station 4 for a new set of assembly operations.

$T_{casmb} = \{T_j\}_{j=\overline{20,26}}$ representing the set of discrete transitions associated with the production flow on the FMC, including the transport of the finished products to the quality control point for verification.

$T_{dataT1} = \{T_k\}_{k=\overline{27.34}}$ representing the discrete transition associated with the flow of information about the Type 1 product.

$T_{dataT2} = \{T_v\}_{v=\overline{35,51}}$ representing the discrete transition associated with the flow of information about the Type 2 product.

The input of the incidence function mathematical form is represented by

$$I_{FMS} : P_{FMS} \times T_{FMS} \to Q_+$$

and the output of the incidence function by

$$O_{FMS} : P_{FMS} \times T_{FMS} \to Q_+$$

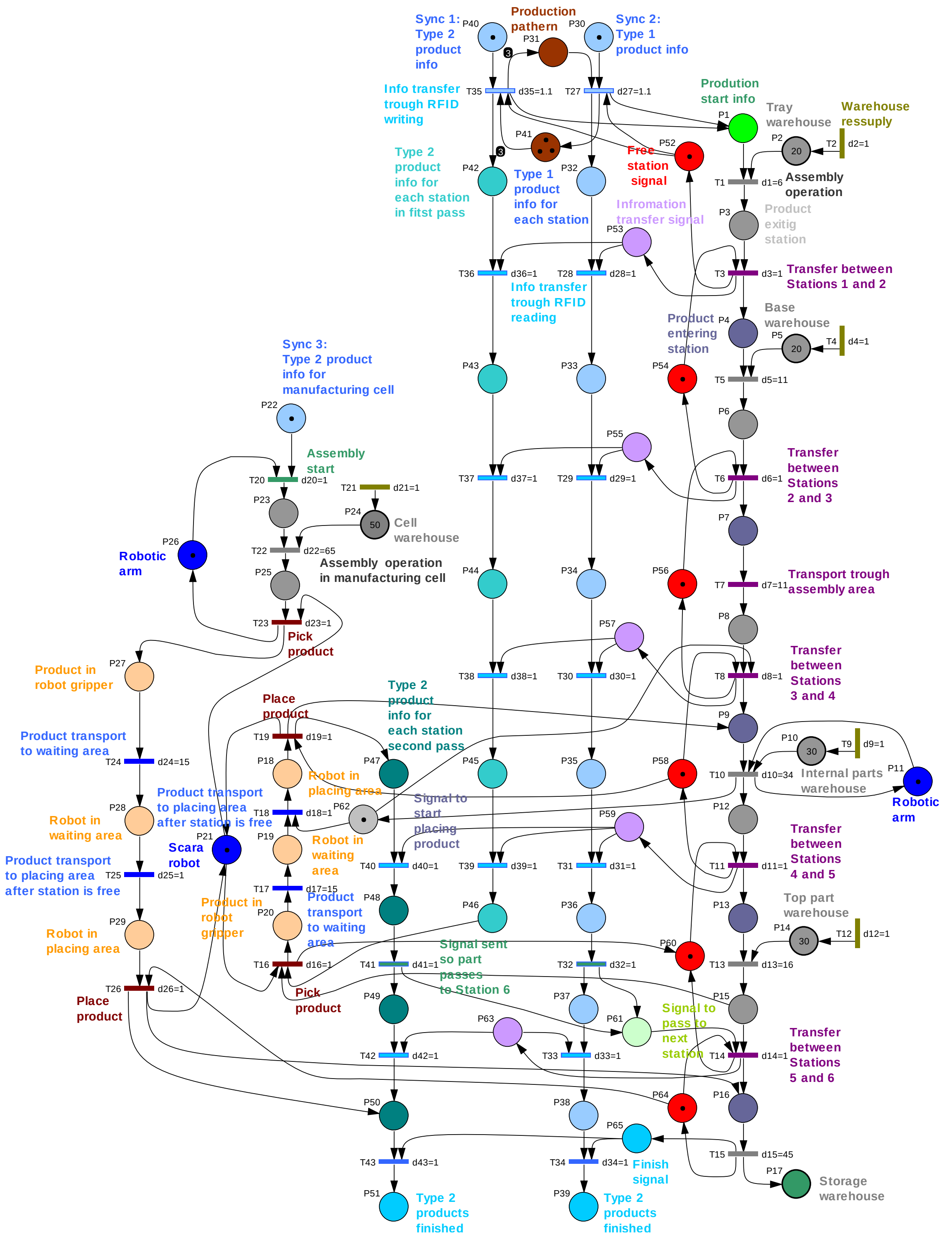

Figure 4. Modelling of FMS manufacturing process.

The temporal values of the transitions are represented by

$$temp_{FMS} : T_{FMS} \to Q_+ \cup \{0\}$$

The external events used in the production flow, represented by the set E_{dFMS} with

$$E_{dFMS} = \left\{E^1_{dFMS},\ E^2_{dFMS},\ E^3_{dFMS}\right\} \cup \left\{e_{FMS}\right\}$$

Function $Sync_{FMS}$ represents the correlations of the sets of information transmission transitions to the set of external events

$$Sync_{FMS} : \left\{\mathrm{T}_{20},\ \mathrm{T}_{27},\ \mathrm{T}_{35}\right\} \to \left\{E^1_{FMS},\ E^2_{FMS},\ E^3_{FMS}\right\} \cup \left\{e_{FMS}\right\}$$

with "e_{FMS}" representing a continuous occurring event, representing a neutral element of the monoid E^*_{dFMS} having:

$$Sync1_{FMS} : T_{35} \to \left\{E^1_{dFMS}\right\}$$
$$Sync2_{FMS} : T_{27} \to \left\{E^2_{dFMS}\right\}$$
$$Sync3_{FMS} : T_{20} \to \left\{E^3_{dFMS}\right\}$$

with

$E^1_{dFMS} = Sync1_{FMS}$ synchronization signal for the transmission of information about the Type 2 product from the optimization algorithm to the FFM production flow.

$E^2_{dFMS} = Sync2_{FMS}$ synchronization signal for the transmission of information about the Type 1 product from the optimization algorithm to the FFM production flow.

$E^3_{dFMS} = Sync3_{FMS}$ synchronization signal for the transmission of information about the Type 1 product from the optimization algorithm to the FMC production flow.

For the process of receiving the production information from the client the mathematical Petri net model can be expressed as:

$$SPN_{recv} = \left\langle TPN_{recv},\ \mathrm{E}_{drecv},\ \mathrm{Sync}_{recv}\right\rangle$$

with the time Petri net

$$TPN_{recv} = \left\langle P_{recv}, \mathrm{T}_{recv},\ \mathrm{I}_{recv},\ \mathrm{O}_{recv},\ m_{0recv}, \mathrm{temp}_{recv}\right\rangle$$

having the places set space

$$P_{recv} = \left\{P_{\mathrm{int}},\ \mathrm{P}_{opt}, \mathrm{P}_{ctrecv}\right\}$$

where:

$P_{\mathrm{int}} = \left\{P_i\right\}_{i=\overline{1,6}}$ representing the discrete places related to the operation of receiving the products information from the client trough a web interface.

$P_{opt} = \left\{P_j\right\}_{j=\overline{7,10}}$ representing the set of places associated to the processing of the received and remained information about the products to obtain an optimal manufacturing sequence to be sent to the flexible manufacturing system.

$P_{man} = \{P_{11}\}$ representing the discrete place associated with the FMS production duration.

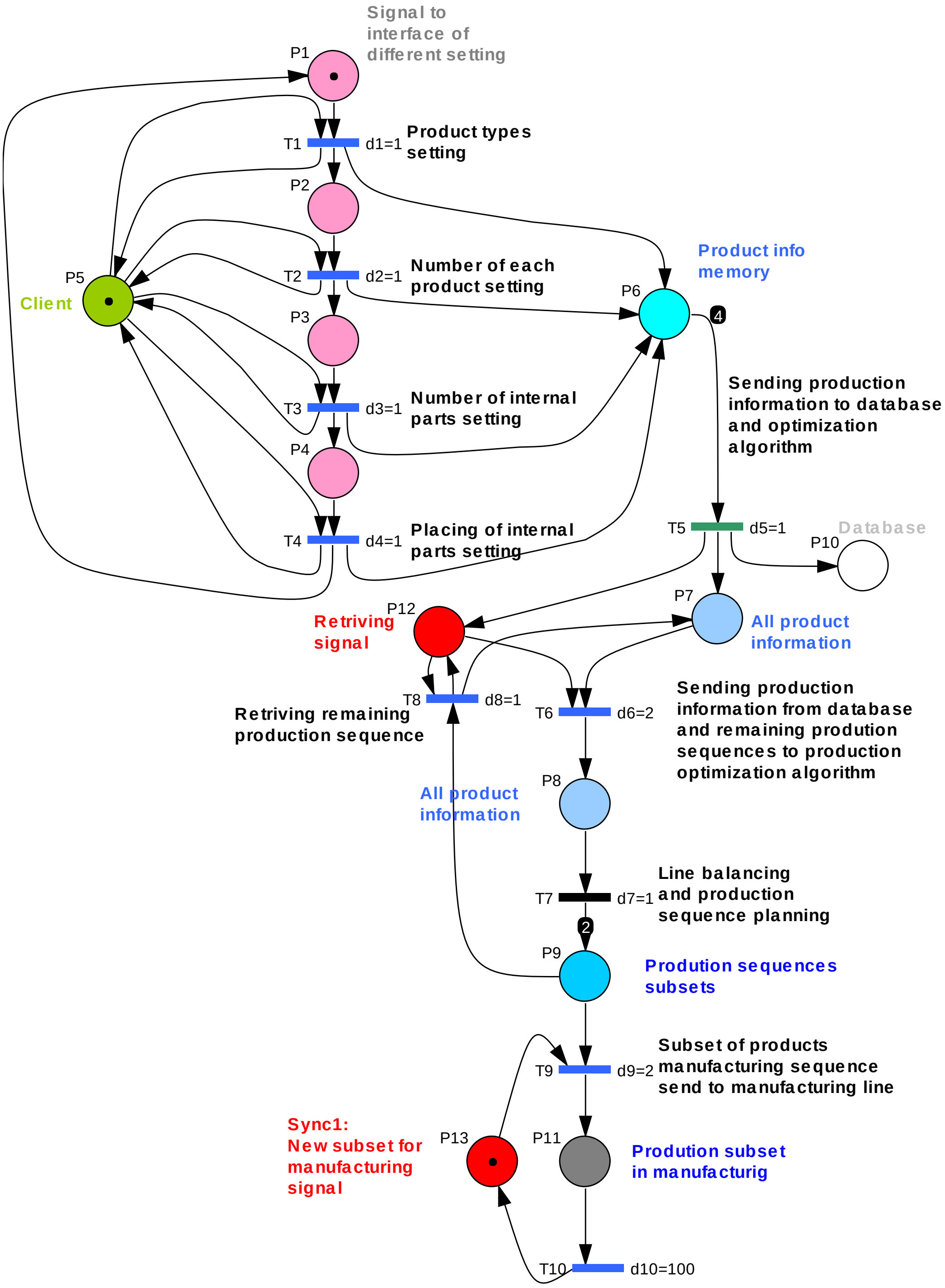

Figure 5. Receiving production information from client and generating the manufacturing sequence.

$P_{ctrecv} = \{P_{12}, P_{13}\}$ representing the discrete places associated to the control function related to a decision action, in this case the reading of manufacturing sequences not sent to the FMS and the sending of manufacturing sequences to the FMS if it is free.

The transitions set space of the Petri net is represented by

$$T_{recv} = \left\{ T_{\text{int}},\ T_{opt},\ T_{man} \right\}$$

with:

$T_{\text{int}} = \left\{ T_i \right\}_{i=\overline{1,4}}$ representing the set of discrete transitions related to the process of retrieving information from the client.

$T_{opt} = \left\{ T_j \right\}_{j=\overline{5,9}}$ representing the set of discrete transitions associated with the processing the product information and obtaining the optimal manufacturing sequence.

$T_{man} = \left\{ T_{10} \right\}$ representing the discrete transition associated with the manufacturing process duration.

The input of the incidence function mathematical form is represented by

$$I_{recv} : P_{recv} \times T_{recv} \to Q_+$$

and the output of the incidence function defined by

$$O_{recv} : P_{recv} \times T_{recv} \to Q_+$$

The temporal values of the transitions are represented by

$$temp_{recv} : T_{recv} \to Q_+ \cup \left\{ 0 \right\}$$

The set of external events, represented by E_{drecv}, can be defined as

$$E_{drecv} = \left\{ E^1_{drecv} \right\} \cup \left\{ e_{recv} \right\}$$

The function $Sync_{recv}$ relates the sets of information transmission transitions to the set of external events

$$Sync_{recv} : \left\{ \mathrm{T}_9 \right\} \to \left\{ E^1_{drecv} \right\} \cup \left\{ e_{recv} \right\}$$

with "e_{recv}" representing a continuous occurring event, representing a neutral element of the monoid E^*_{drecv} having:

$$Sync1_{recv} : T_9 \to \left\{ E^1_{drecv} \right\}$$

with

$E^1_{drecv} = Sync1_{recv}$ the synchronization signal for the transmission of the next manufacturing sequence to the flexible manufacturing system, as the system starts producing the last product of the previous sequence.

3.2. *SIMULATION OF THE FLEXIBLE MANUFACTURING SYSTEM*

Based on the developed model a simulation of the FMS production flow can be made. In Fig. 6 can be observed the simulation for the FMC and the 6 Stations FFM production flow. In the presented simulation was considered the production of the Type 1 product on the FMC and the production of a Type 1 and a Type 2 products on the FFM. The production of a Type 1 product stats at the same time on the FFM and FMC, based on the optimisation algorithm results.

The FMC product, given the manufacturing and transportation durations arrives at the exit of Station 5 and enters Station 6 quality control area as the FFM product arrives to the picking area on Station 5, ensuring the minimisation of waiting times.

Also, in Fig. 6 can be observed the transportation of the FFM Type 1 product from Station 5 back to Station 4 by the SRTS. This transportation can induce waiting times in Station 3 if a product needs to enter Station 4. Beside the waiting times introduced by placing a returning product to Station 4, waiting times are introduced in the stations that have the production durations smaller than the largest production duration. This waiting times can’t be eliminated given the FMS structure.

Along with the verification of the waiting times and synchronization of the FFM and FMC production flows, the simulations ensures that no bottlenecks are obtained. This is especially important in the transportation of the Type 1 products from FMC and FFM using the SRTS. For a better use of the SRTS the FMC product is picked first and placed in the picking area of the FFM product, ensuring a reduction in process duration.

The manufacturing sequence is determined by an optimisation algorithm and becomes especially relevant in large productions by minimising the waiting time introduced by the transportation of products between FMC and FFM. The information needed by the algorithm is received directly from the client and processed using cloud computing technology, the FMS receiving only the manufacturing sequence for a portion of the client request.

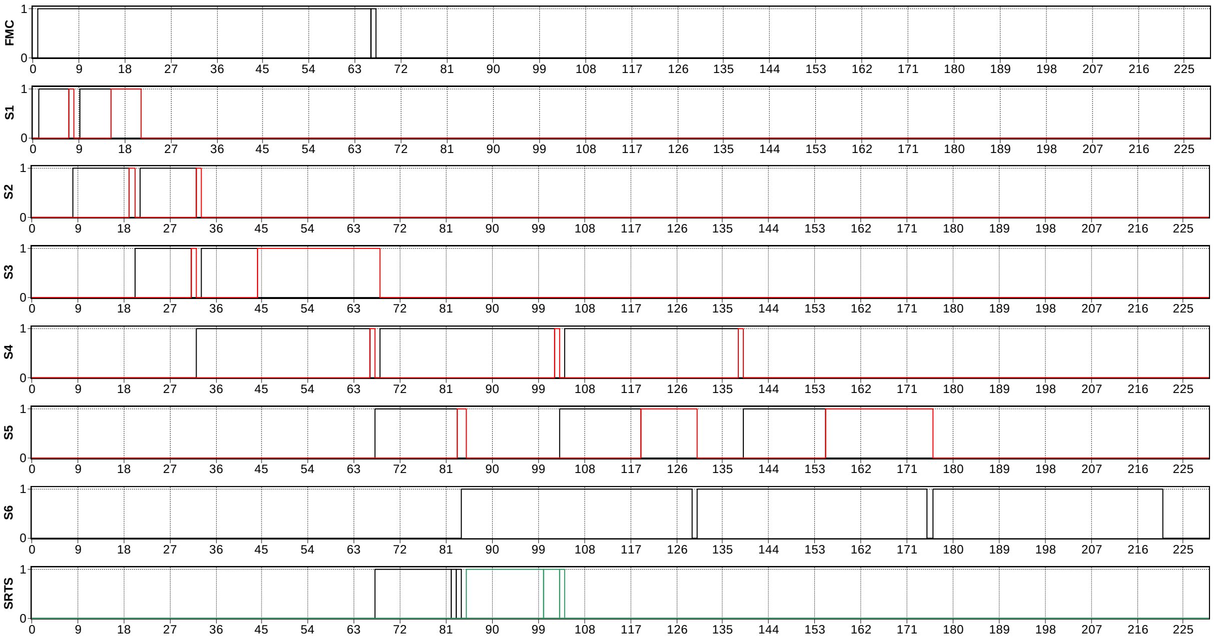

Figure 6. FMS production flow simulation.

4. CONCLUSIONS

In the current manufacturing environment, the client demand becomes increasingly more dynamic. This moves the manufacturing paradigm from a mass production paradigm to a personalized production paradigm. For this porpoise the manufacturing systems need to be capable of integrating with ease new production technologies and capabilities. The possibility of integrating new equipment and technologies needs to be considered from the design or redesign of the production capabilities.

In manufacturing system design and redesign, the modelling stage is crucial for creating efficient production capabilities. By building a model of the system, weaknesses can be quickly identified, and bottlenecks can be eliminated from the design stage through simulations. Additionally, the system model can be modified to accommodate the desired optimization algorithm output, which enhances the redesign process's optimization.

This paper proposes a Petri net model of a flexible manufacturing system that can produce two types of customizable products using in-line and in-cell production capabilities. The developed model showcases the production and data flow for the two product types on the two parallel manufacturing processes. Furthermore, the paper proposes a model for receiving production data directly from the client through a designated web interface, ensuring a fully automated production process that shortens the manufacturing process's time from request to production start.

The developed models and simulations are utilized in the control strategy of the manufacturing system. As Petri nets focus on the decision functions represented by the transitions, a controller development based on the model obtained was easily made. This paper's models also facilitate the development and implementation of new optimization algorithms through simulation capabilities. Overall, the proposed model provides a comprehensive framework for designing, controlling, and optimizing flexible manufacturing systems, contributing to the field.

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