IOSUD – „DUNĂREA DE JOS” UNIVERSITY OF GALAȚI

Doctoral School of Fundamental Sciences and Engineering

DOCTORAL THESIS

Application of Industry 4.0 and 5.0 concepts to the modelling and control of flexible manufacturing processes

Summary

PHD CANDIDATE,

Ing. Octavian-Gabriel DUCA

Scientific Coordinator,

Prof. dr. ing. Eugenia MINCĂ

Seria I 8: Systems engineering Nr.10

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Preface

This thesis is the result of the research activity from October 2019 to March 2023 in the field of Systems Engineering within the Faculty of Automation, Computers, Electrical and Electronic Engineering of the University "Dunărea de Jos" in Galați.

I mention that the theoretical research, the experimental activity, the conception/drafting of the doctoral thesis were carried out with the logistical and financial support provided by the complex project UEFISCDI CIDSACTEH, project number PN-III-P1-1.2-PCCDI-2017-0290, in which they collaborated research teams from the "Dunărea de Jos" University - coordinator, the Valahia University of Târgoviște, the Politehnica University of Bucharest and the University of Craiova.

I would like to express my deep gratitude to the doctoral supervisor, Mrs. Prof.dr.ing. Eugenia Mincă for the guidance given, involvement and recommendations made and for the moral support and understanding offered throughout this research period.

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Last but not least, I thank my family for their unconditional support, understanding and love during this period, which motivated me and created the right conditions to complete my PhD thesis.

I would like to thank all those who, directly or indirectly, helped and supported me during these years in which I developed this work.

Thank you very much!

Galați, April 2023
Ing. Octavian Gabriel DUCA

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Notations and Abbreviations

IoT - Internet of Things
IoE - Internet of Everything
IoS - Internet of Services
RFID - Radio Frequency Identification
ERP - Enterprise Resource Planning
CPS - Cyber-Physical System
XaaS - Anything as a Service
DBaaS - Database as a Service
KaaS - Knowledge as a Service
BPaaS - Business Process as a Service
SaaS - Software as a Service
PaaS - Platform as a Service
IaaS - Infrastructure as a Service
RPT - Timed Petri Nets
RPS - Synchronized Petri Nets
IFS - In Flux System
QC - Quality Control
IFMS - Integrated Flexible Manufacturing System
FFM - Flux Flexible Manufacturing
FMC - Flexible Manufacturing in Cell
SCARA - Selective Compliance Articulated Robot Arm
SRTS - SCARA Robotic Transportation System
PLC - Programmable Logic Controller
PID_E - Event triggered PID

Introduction

In recent years, interest in the new industrial revolution, called Industry 4.0, has grown significantly. This revolution integrates a set of advanced concepts - Smart Factory, Big Data, Augmented Reality, Cyber-Physical Systems, Internet of Things (IoT) and Internet of Everything (IoE), which bring radical changes in the hardware structure of systems but and in the structure of control architectures.

The concepts of Industry 4.0 are the basis for the development of the next stage of industrial evolution, Industry 5.0, which is rather complementary to the concepts of 4.0. Industry 5.0 brings the human factor back into the equation of industrial ecosystems, promoting the integration of the operator at the centre of industrial processes. This evolution focuses on aspects of sustainability, ethics, diversity and low environmental impact, proposing a complete paradigm shift.

Stages of industrial evolution up to Industry 4.0

Since ancient times, significant production activities - agriculture, transport or textile production - were carried out by manual labour. This production method required a long process of product development and improvement, mainly achieved through successive trials, with the aim of eliminating errors. An important event in the history of industrialization was represented by the first industrial revolution, also called Industry 1.0.

The first industrial revolution took place in the second half of the 18th century and lasted until the middle of the 19th century. This revolution was influenced by the advent of the water pump and the steam engine, which enabled the mechanization of production processes and the transformation of manual production systems into manufacturing systems [1, 2]. The use of steam engines enabled the extraction and production of goods in a much shorter time.

The second industrial revolution, known as Industry 2.0, started at the end of the 19th century and lasted until the beginning of the 20th century [1, 3]. This stage of transformation was influenced by the advent of electricity and the development of the division of labour [2, 4]. These elements allowed the manufacture of products on production lines

Between the 1960s and the beginning of the 21st century [2], the third major stage in the evolution of production took place, called Industry 3.0. This industrial revolution, also known as the digital revolution [1], sought to use information technology and electronic circuits to increase productivity and improve production processes [4, 2, 1].

Concepts and technologies specific to Industry 4.0 integrated into flexible manufacturing processes

The concept of Industry 4.0 was introduced at the Hanover Trade Fair in 2011, although some sources claim that the fourth industrial revolution began at the beginning of the 21st century. According to specialized literature, this industrial evolution is characterized by the integration of artificial intelligence in production processes, but in general it is considered as having as its main purpose the increase of efficiency and productivity of manufacturing systems [5].

To achieve the desired level of efficiency and productivity of industrial processes, a number of new technologies have been implemented, including Augmented Reality, Big Data analysis, Cyber-Physical Systems, Cloud computing and the Internet of Everything, among others. All these technologies are used to reconfigure production systems, in models with a hierarchical structure, called 5C [6]. The hierarchical model includes the following levels:

- Connection (Connectivity);
- Communication (Communication);
- Coordination (Coordination);
- Cooperation (Cooperation);
- Collaboration (Collaboration).

By integrating a set of technologies, designed in accordance with the above concepts, the concept of "Smart Factory" (Smart Factory) emerged, which allows the manufacture of products with advanced features, through the use of intelligent procedures and processes.

Smart Factory

The Smart Factory concept proposes an innovative approach that integrates modern production technologies, with the potential for application in various industrial fields. Using this approach leads to the development of intelligent, safe, efficient and sustainable production systems in terms of environmental impact [16]. According to [18], the Smart Factory concept allows the development of adaptable and flexible production systems that will integrate products and machines with autonomous and intelligent action abilities, thanks to the integration of Industry 4.0 specific concepts, such as the Internet of Everything or Cyber-Physical Systems.

Cyber-Physical System (CPS)

A CPS, defined in [20], is a set of interconnected physical and cyber resources that use intelligent automatic control to improve the autonomy and efficiency of the entire system. The components of CPS are characterized by a close interaction between a cybernetic component (software) and a physical one (devices), both of which are essential for obtaining a high level of performance, robustness, efficiency and reliability in the production environment [21, 22].

Internet of Everything

The Internet of Things (IoT) concept is the customization of the Internet of Everything (IoE). Physical devices are interconnected in a network with intercommunication capabilities [32]. The purpose of IoT is to facilitate communication, especially wireless communication, between commonly used devices [33].

Cloud Computing

The Cloud computing paradigm was introduced as a new method of distributing the computing power of devices in a network. In the reference architecture proposed by the US National Institute of Standards and Technology, Cloud computing can be divided into three service models: software as a service - Software as a service (SaaS), platform as a service - Platform as a service (PaaS) and infrastructure as a service - Infrastructure as a service (IaaS), which allow users to access software services, operating systems, tools or hardware elements via the Internet [38, 39].

Vertical and horizontal system integration

Systems integration is the process of interconnecting all components of a system in a coherent operational way, involving software, hardware and other systems and subsystems [42]. In Industry 4.0, the integration of components and systems is achieved through specific technologies, such as IoT, so that devices can communicate with each other, coordinate and collaborate within processes [32, 44]. This integration can be done by [5]:

- Horizontal integration;
- Vertical integration;
- End-to-end integration.

Concepts and technologies specific to Industry 5.0, integrated into flexible manufacturing processes

In a world in continuous industrial evolution, Industry 5.0 emerged as a complementary reaction in relation to systems developed on 4.0 concepts, proposing a better integration of humans in industrial processes. The concept of Industry 5.0, introduced in 2020 by the European Commission [45] represents a new industrial evolution, which proposes a modified vision for the way in which the industrial process is generically approached, implicitly the manufacturing system.

At the core of this new industrial evolution are the concepts of human-centeredness, sustainability and resilience. The basic idea, in Industry 5.0 approaches, is to select technologies in coordination with an ethical reasoning, relative to how these technologies support human values and needs.

Research objectives and systematic evaluation of results

The objectives proposed for this research project aim at the design and implementation of techniques for adapting a production line from a system intended for flow manufacturing to a system for flexible manufacturing, with the integration of the concepts of Industries 4.0 and 5.0. In this sense, the following specific objectives have been identified:

OB.1. Hardware design and adaptation techniques of a production line dedicated to flow manufacturing, to an integrated system for flexible manufacturing, with the integration of Industries 4.0 and 5.0 concepts;

OB.2. Modelling and implementation of the management of the integrated system for flexible manufacturing, subordinated to the concepts of Industries 4.0 and 5.0, with an emphasis on IoT and Digital twin;

OB.3. Automatic control of the integrated system for flexible manufacturing, for the realization of transportation, positioning and disturbance compensation operations in stations, and the integration of the concepts of Industries 4.0 and 5.0;

OB.4. Designing the optimal scheduling of hybrid manufacturing, on a line with parallel production flows, with the following sub-objectives;

OB.5. Implementation of the optimal planning algorithm of hybrid manufacturing on ISFM, with the integration of the concepts of Industries 4.0 and 5.0.

The structure of the thesis by chapters

In this work, the research focused on the design and implementation of techniques for adapting production lines intended for flow manufacturing to integrated systems for flexible manufacturing with the integration of Industries 4.0 and 5.0 concepts for efficient management.

The first chapter presents the fundamental notions for production systems dedicated to flow manufacturing, as well as specific aspects of laboratory manufacturing, in a related approach to Industries 4.0 and 5.0. In addition, the two subsystems obtained by designing the processes of flexible manufacturing in flow and flexible manufacturing in the cell are presented. Also, the hardware structure of the system that unitarily integrates the two structures for flexible manufacturing, obtained as a result of the design, is described.

In Chapter 2, modelling with RPS, integrated system dynamics for flexible manufacturing, applying IoT and Digital twin concepts, and workstations is proposed. Moreover, the RPS models of the manufacturing process of the 6 stations involved in the assembly process are presented.

Chapter 3 focuses on the design and implementation of a PID control structure, transport operations, and precise disturbance-compensated positioning for workstations. A variant of the control algorithm with conventional PID structure is proposed, as well as an event-based PID algorithm (PID_E). To validate the control structure, simulations of automatic transport control and accurate positioning with disturbance compensation are performed. Finally, the implementation of automatic control is carried out, with the application of Industry 4.0 and 5.0 concepts.

In Chapter 4, the design of an optimal production task scheduling algorithm for an integrated flexible manufacturing system with two parallel production flows is presented. Customizations of this algorithm for the flexible manufacturing laboratory system are also detailed. The algorithm is validated by simulations of the tasks distributed on the two flows, based on the results provided by the optimal planning, tested on production scenarios.

Chapter 5 is dedicated to the implementation of the optimal planning algorithm with the collection of manufacturing data through a unitary Client-Server software platform. The platform provides, through the Cloud server, the dynamic interface between the optimal manufacturing planning algorithm and the real-time takeover of production tasks and orders. Aspects of the concepts of Industries 4.0 and 5.0, which are found in implementation, are highlighted.

Chapter 6 provides a synthetic presentation of the conclusions and scientific contributions, which we judge in relation to the proposed theme and objectives. In addition, future research directions are presented, through which the research developed in the thesis can be continued, relative to new technologies for flexible manufacturing. Finally, it quantifies the gain offered by the solutions for improving planning, optimizing production, and the extensive implementation of the concepts of Industries 4.0 and 5.0. The dissemination of the obtained research results represents the validation of the original concepts and new technologies presented in the Thesis, by the scientific community in the field.

Chapter 1

Techniques for adapting lines for flow manufacturing to integrated systems for flexible manufacturing, in a specific approach to Industries 4.0 and 5.0

In the development process of manufacturing systems, the design of the system configuration involves the consolidation of a hardware work structure, appropriate to the technology of the execution of products, as well as the identification of tasks in the use of equipment, as subordinate modules. This correlates with the characteristics of the manufacturing process, the cycle time, the number of stations and equipment used, as well as the allocation of workloads to operations and execution sequences [48].

1.1. Production systems for flow manufacturing

Sequential manufacturing systems, also called flow manufacturing systems, are production systems that work according to a specific technology to assemble a type of product. Operations are carried out in sequentially interconnected stations configured to be used in repetitive processes so as to maximize efficiency and productivity. A characteristic of these systems is the specialization of the stations on unique operations, each workstation, in the production line, being dedicated to carrying out a specific operation.

1.1.1. Characteristics of systems for flow manufacturing

For manufacturing systems, the number and diversity of finished products is an essential characteristic. If a single type of product or products derived from it, with similar structure of components, is produced, the system is assimilated with a production line adapted to the manufacture of products with unique typology [49]. However, modern manufacturing systems can produce multiple product typologies as well as typologies derived from the base product [50, 51].

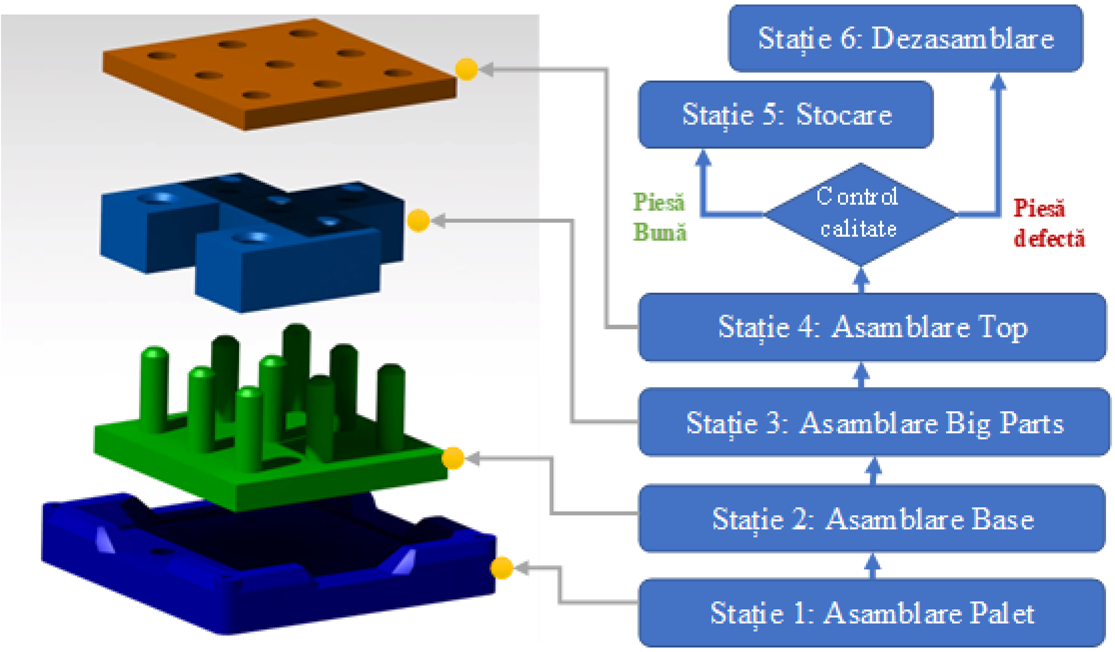
In such situations, a mixed production line can be implemented, on which products belonging to a product family as a typology can be manufactured. The manufacture of these products respects arbitrarily determined sequences of operations, or based on an algorithm [52].

If it is necessary to reconfigure the system, in order to be able to produce several typologies, the production sequences are applied in batches, for each typology of product [52].

1.1.2. Flow manufacturing and hardware structure of the laboratory system

Laboratory systems for flow manufacturing are didactic or research systems, with a structure similar to real systems, but with reduced dimensions of work capacities or service systems [79].

The product made on the laboratory production line (Figure 1) has a structure of components arranged on three layers, placed in assembled form on the pallet. The first layer is represented by the base of the product (base). The second layer consists of a set of intermediate parts (big parts). The third layer is represented by the product cover (top).



a) b)

Figure 1. a) Components of the product assembled on the laboratory production line; b) Block diagram related to the sequence of manufacturing operations in flow.

The data related to the operations required to manufacture the product are stored on an RFID tag embedded in the pallet. This data is used during the execution of assembly operations, quality testing, storage.

Manufacturing management is carried out by means of PLCs integrated in each workstation (Figure 2). Thus, each station works independently, communicating the necessary information to the other stations. The communication between the PLCs is done through the ProfiNet protocol, and the connection with the physical execution components of the stations is done through the input/output ports.

A human-machine interface (HMI) connected to the system's ProfiNet network allows the operator to enter the current manufacturing specific data, number of products and the configuration of the intermediate parts layer for each product.

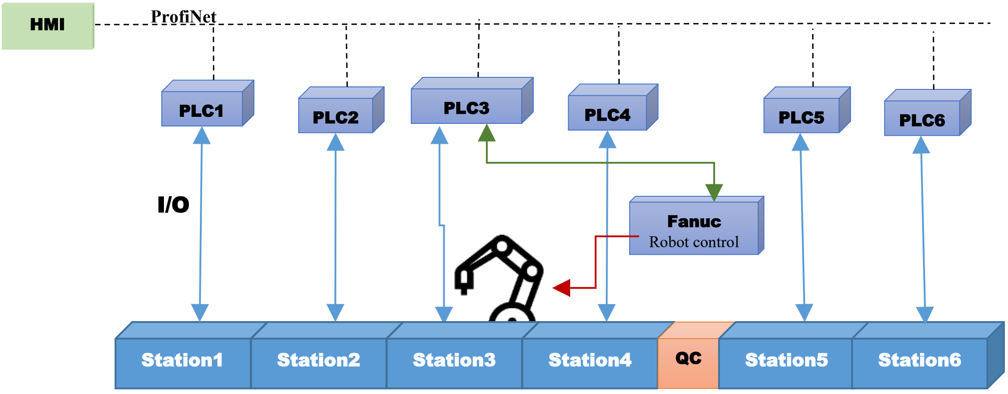


Figure 2. Manufacturing line management system architecture

1.1.3. RPS modelling of flow manufacturing

The analysis of the manufacturing flow system (IFS) dynamics, served by the FANUC robotic manipulator, is based on the process associated model. By using the Synchronized Petri Nets (RPS) modelling tool it was obtained:

$$RPS_{IFS} = \langle RPT_{IFS},\ E_{IFS},\ Sync_{IFS} \rangle, \tag{1.1}$$

The Sync_{IFS} function conditions the execution of some transitions on the reception of external events:

$$Sync_{IFS} : \{T_1\} \rightarrow \left\{E^1_{IFS}\right\} \cup \{e_{IFS}\}, \tag{1.2}$$

with e_{IFS} the neutral event embedded in the monoid E^*_{IFS}. Thus it can be defined

$$Sync1_{IFS} : T_1 \rightarrow \left\{E^1_{IFS}\right\}, \tag{1.3}$$

where $E^1_{IFS} = Sync1_{IFS}$ represents the synchronization signal between the start of the manufacturing process and the end of the data acquisition process.

1.1.4. RPS model simulations to determine flow manufacturing specific parameters

Following the simulation of the RPS model, information is obtained that describes the sequence of operations and the waiting times for the assembled products. The simulation results are presented in Figure 5, representing the durations in which the product is involved in an active or standby operation.

Following the simulation of the process, it is observed that the waiting times, during the initialization period, of each part are zero until the moment when the station with the longest operating time is reached. The high execution times in Station 3 generate a bottleneck effect that propagates to previous stations. By default idle times are generated in connected stations in positions succeeding Station 3.

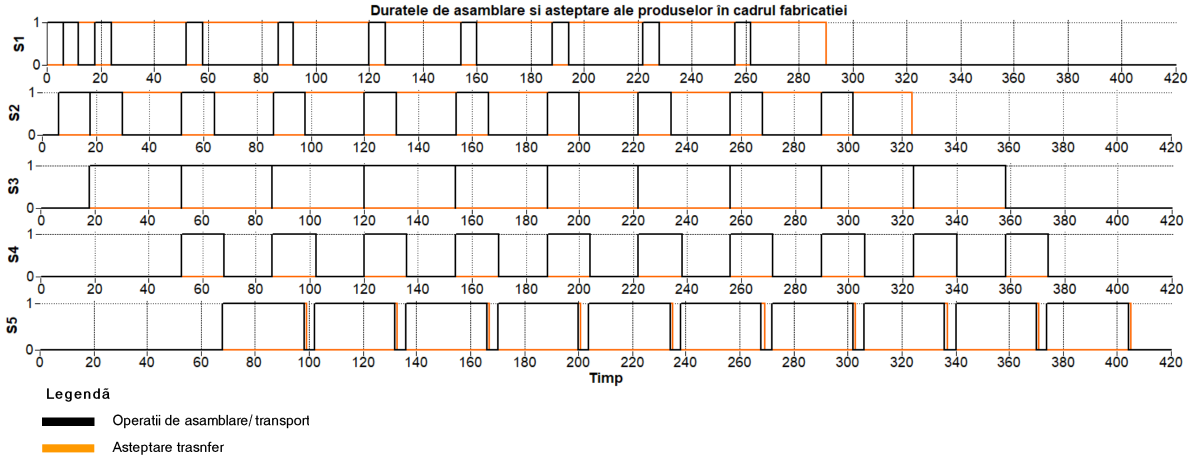


Figure 3. Durations of operations for assembling a product, from stations S1-S5

1.2. System adaptation techniques for flow manufacturing to flexible manufacturing with the application of Industries 4.0 and 5.0 concepts

Systems for flexible manufacturing can produce a varied range of products, derived from specific types of manufacturing ranges. Manufacturing is flexible in the sense that, on the same production system, products with different typologies can be made.

By introducing a manufacturing cell, managing the manufacturing process acquires the attribute of resilience, in the sense of integrating the function of compensating for disturbances that may occur during manufacturing, ensuring continuous manufacturing. A process designed to operate on parallel flows has continuous manufacturing capability, which provides the solution to switch manufacturing to an alternate flow if the current flow breaks down.

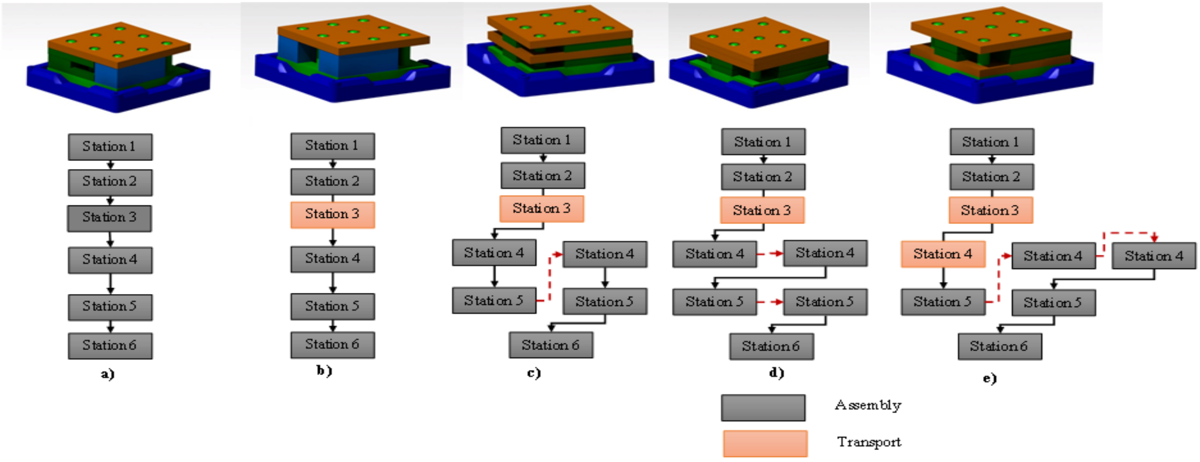


Figure 4. Succession of operations in stations for flexible and flow manufacturing. a) Flow manufacturing served by MR1, MR2, of a Type 2 product; b) Flow manufacturing served by an MR2, of a Type 2 product; c), d) e) Flexible manufacturing served by MR2, for Type 1 products, with repetition of operations from Stations 4, 5, in different combinations

Therefore, it can be considered to expand the initial range of products shown in Figure 1 by introducing the additional small part component, so that it is possible to manufacture four more types of products, for a total of five typologies (Figure 6).

Within this research work, two types of products from a potential range of five were analysed, namely the initial part Type 2 (Figure 6.b.), and a new part with a multilayer structure, Type 1 (Figure 6.c.).

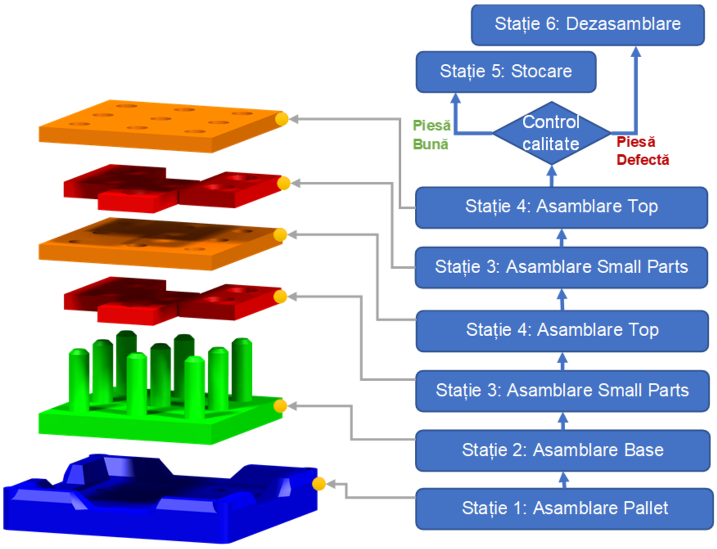
1.2.1. System Hardware Design for Flexible Flow Manufacturing

The realization of techniques for adapting the flow manufacturing process to one for flexible flow manufacturing (FFM) started from the assumption that two types of products, Type 1 and Type 2, will be manufactured on the same production system, with balanced demand of production resources. The design of the process involved the development of two systems for flexible manufacturing, intended for parallel manufacturing:

- stage 1: the introduction of an additional transport system was analysed, in a direction parallel to the direction of the flow of interconnection of the stations, which would carry out the operations of transport and positioning of the product in the stations, according to the product execution technology;
- stage 2: the introduction of a parallel production process was considered by implementing a flexible manufacturing cell (FMC) as an "integrated station" in the flow manufacturing system. Therefore, the structure of successive connection of the stations is maintained, with one of the stations having maximum potential for adapting to flexible manufacturing.

Considering the previous hypothesis and proposals, a comparison was made between the assembly process of a Type 2 product (Figure 1) and a Type 1 product (Figure 7).

To transport the product to the stations, or to repeat some assembly operations, according to the execution sequences of the product, a transport system equipped with a SCARA robot was implemented.



a) (b)

Figure 5. a) Type 1 product components assembled on IFMS; b) Block diagram of the planning of multi-layer product assembly operations, on IFMS

Thus, in the second iteration of the development of techniques for adapting flow manufacturing to flexible manufacturing, the production system will use the hardware structure composed of seven workstations (Figure 9) and a transport system, parallel to the transport from stations.

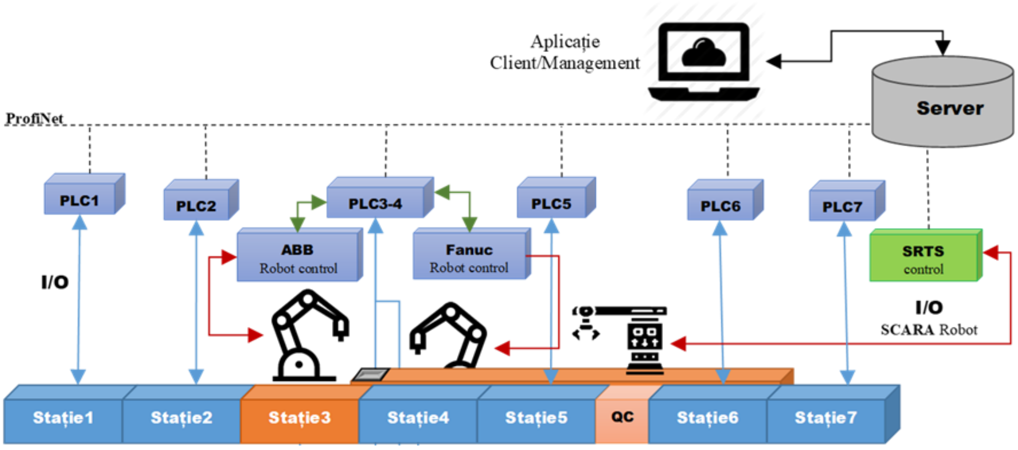


Figure 6. Integrated System for Flexible Flow Manufacturing (FFM) and Flexible Manufacturing in the Cell (FMC)

In the case of assembly of Type 1 products, the first intermediate top will be placed in station 5, the partially assembled product is transported back, via the SCARA robotic transport system (SRTS), to Station 4, where a new set of assembly operations is initiated of small parts components (Figure 10). Following the assembly in Station 5 of the top component – the last component, the product is transported to Station 6 for quality control. If the product is compliant, it is stored in the warehouse related to Station 6. Otherwise, the defective product is transported for disassembly. The process within Station 6 is similar for Type 1 and Type 2 products.

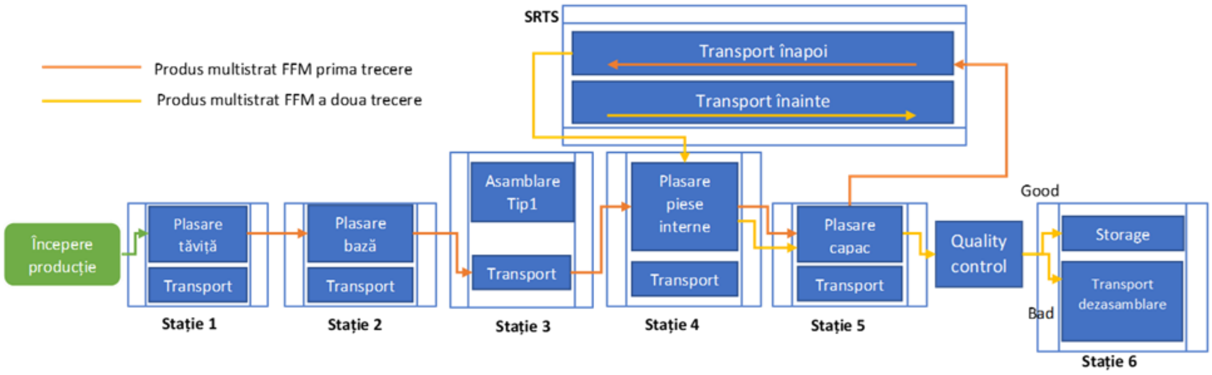


Figure 7. The sequence of assembly and transport operations for the manufacture of a Type 1 product on FFM

1.2.2. Manufacturing in the flexible cell as a sub-process of manufacturing on IFMS

For flexible manufacturing in the cell (FMC), a system was designed that allows full assembly and disassembly of products (Figure 11), by means of ABB's specialized robotic arm. Only Type 1 products are assembled in the flexible cell. Component warehouses are positioned inside the cell, close to the robotic arm.

The ABB manipulator picks up the necessary components and successively performs the assembly operations. If the assembly process is carried out through repetitive operations of handling, transporting and assembling the components, the disassembly in the FMC is carried out by grabbing each component with a gripper or with the vacuum system, and placing it in the appropriate warehouses.

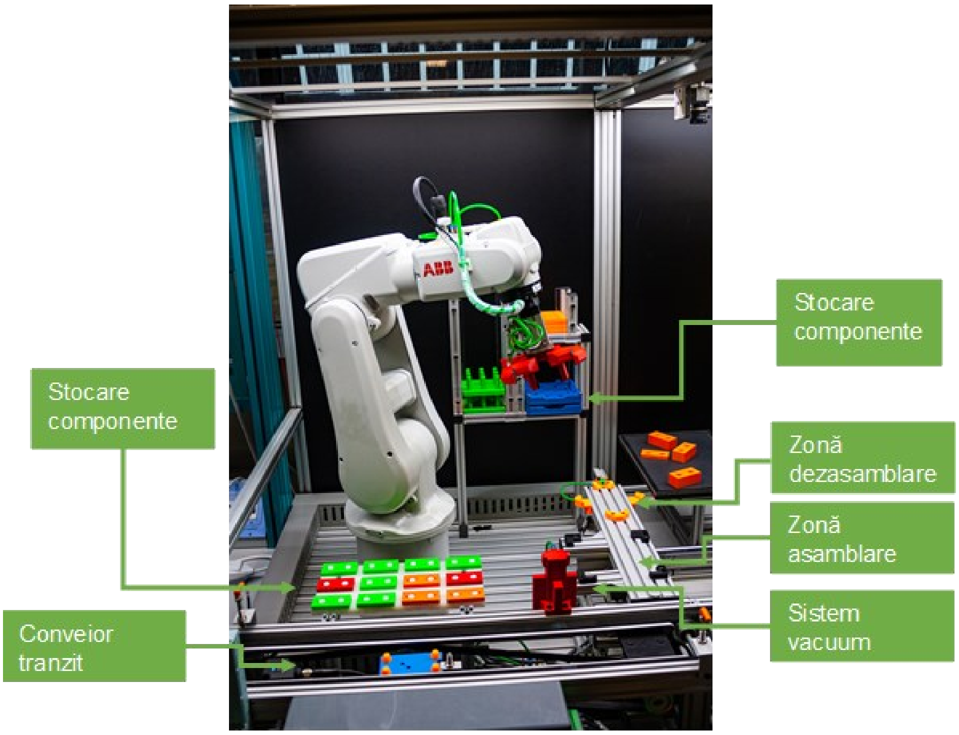


Figure 8. Station 3 – Flexible cell equipped with ABB manipulator

In designing the assembly/disassembly technology on the integrated system for flexible manufacturing, the assumptions are considered: if a defective product was assembled on the FFM, it will be disassembled in Station 7; if a defective product has been assembled in the FMC, it will be transported back to the cell (with SRTS), and fully disassembled in the FMC.

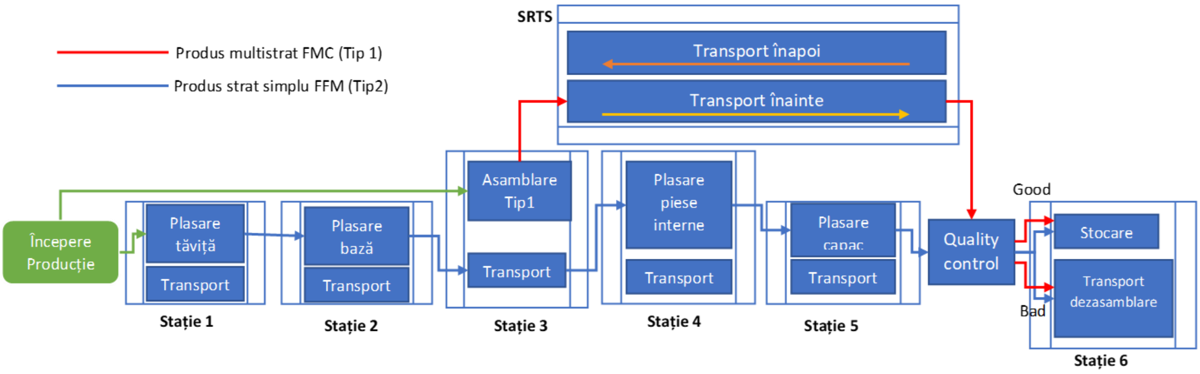
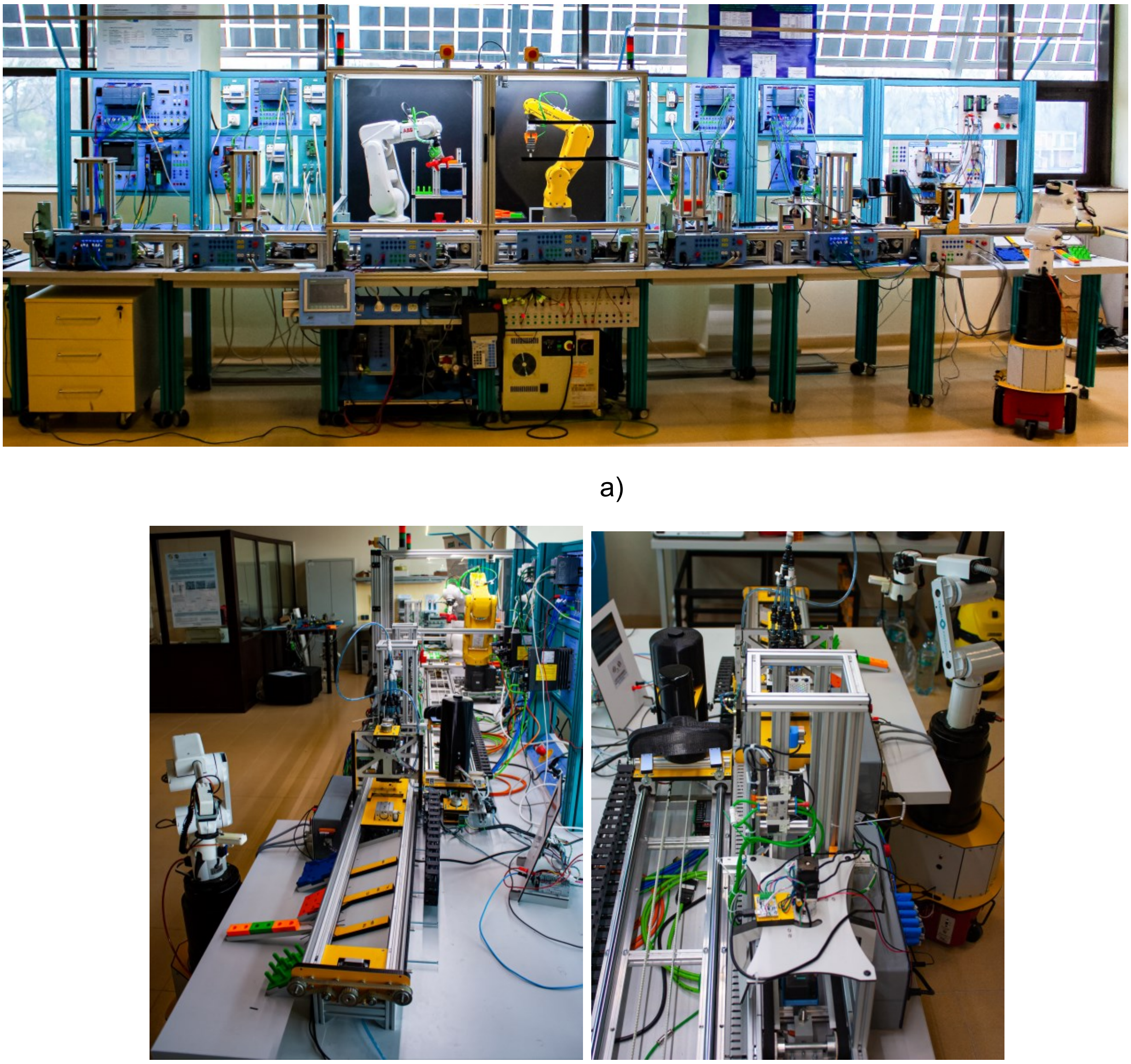


Figure 9. Sequencing of operations for flexible manufacturing in FMC

1.3. Hardware structure of the integrated system for flexible manufacturing with two parallel flows. Application of specific concepts of Industries 4.0 and 5.0

Based on the design of processes for flexible manufacturing in flow and in the cell, an integrated manufacturing system, IFMS_4.0_5.0, subordinated to the concepts of Industries 4.0 and 5.0, was developed (Figure 13). Because IFMS_4.0_5.0 was designed for end-to-end manufacturing, having the ability to perform a full operational cycle of assembly, disassembly, recovery and reuse of components.

Since the research has strictly addressed the flexible manufacturing process, further work will be done on a partial hardware structure - ISFM, dedicated only to flexible manufacturing. The area of recovery, reuse of components, through disassembly, handling, transportation and recovery of products by the Pioneer mobile robot, is a future direction of development.



a)

b) c)

Figure 10. a) IFMS_4.0_5.0 with two parallel proceses, served by three robotic manipulators (ABB, FANUC, SCARA) and one mobile robot (PIONEER); b) Disassembly station from IFMS_4.0_5.0; c) Flexible manufacturing served by the SCARA robotic system

A transport system equipped with a SCARA robot is used to transport products between stations on the manufacturing flow, or between the manufacturing cell and stations on the manufacturing flow.

The communication between the SRTS and the stations of the flexible manufacturing system is realized with the Profinet over Ethernet protocol, through a wireless connection. Thus, this system is an IoT system from the perspective of Industries 4.0 and 5.0 The introduction of the SCARA robot into the transport system was determined by the need to pick up and position products from different locations and with different orientations.

1.4. Scientific results and contributions

In this chapter, the technological design, the hardware design and the implementation of the techniques of adapting a production line for flow manufacturing to an integrated system for flexible manufacturing were carried out. By applying adaptation techniques, the integrated system for flexible manufacturing has been implemented, which has seven independently controlled stations, informationally interconnected through Profinet communication, in its hardware composition. The integrated system for flexible manufacturing can work both as a system intended for the manufacture of products with a unique typology, but also as a system with the ability to adapt to different types of products, from the manufacturing range.

> In this section, the specific objectives of the general objective OB.1 were achieved. Design and implementation of techniques to adapt a production line dedicated to flow manufacturing to an integrated system for flexible manufacturing, with the integration of Industries 4.0 and 5.0 concepts. Thus, the obtained results align with the research directions for achieving the objectives: OB.1.1. The design of hardware adaptation techniques of a line for flow manufacturing, to a line dedicated to flexible manufacturing, with the application of Industry 4.0 and 5.0 concepts; OB.1.2. Designing the hardware structure of the integrated system for flexible manufacturing, dedicated to flexible in-line and cell assembly, with the application of Industry 4.0 and 5.0 concepts.
>
> The conceptual and hardware realization of the Integrated System for flexible manufacturing with attributes specific to Industries 4.0 and 5.0, constitutes a significant scientific contribution with major impact in terms of diversifying production capacities and increasing productivity, with minimal costs. By using an innovative hardware structure, this system demonstrates the commitment to the principles of sustainability and circular economy promoted by Industry 5.0. The integrated system for flexible manufacturing, based on the convergence of physical and cyber resources, integrates the concept of total manufacturing by implementing a complete operational cycle, through the operations of assembly, quality control, disassembly, recovery and reuse of components. This ensures the sustainability of the production system, a component of Industry 5.0 that focuses on the reuse and recycling of natural resources, the reduction of waste and the impact on the environment. The proposed hardware structure, with two parallel work flows, ensures manufacturing resiliency by being able to switch production to the alternate flow when a failure is identified on the mainstream. Thus, through the proposed hardware structure, continuous manufacturing is ensured, thus subordinating the proposal of the concept of production resilience, specific to Industry 5.0.

Chapter 2

Modelling integrated system dynamics for flexible manufacturing from a management perspective with Digital twin

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To model the management of the flexible manufacturing process, specialized tools will be used in the modelling of processes whose dynamics are determined by discrete events, namely Petri Nets (RP). RP typologies will be used in accordance with the type of process considered, its complexity, as well as its interconnection with sub-processes [84]. Thus, for modelling assembly/disassembly processes in workstations, timed RP (RPT) and synchronized RP (RPS) will be used. RPS models will be useful in applying the Digital twin concept to the implementation of real-time control [85].

2.1. RPS modelling of integrated system dynamics for flexible manufacturing with two parallel production flows

Starting from the design of flexible manufacturing systems and processes in flow and in the cell, the model of the integrated flexible manufacturing system can be represented by the synchronized Petri net

$$RPS_{FMS} = \langle RPT_{FMS},\ E_{FMS},\ Sync_{FMS} \rangle . \tag{2.1}$$

The $Sync_{FMS}$ function represents the associations between a set of transitions and the set of external events:

$$Sync_{FMS} : \{T_{20},\ T_{27},\ T_{35}\} \rightarrow \left\{E^{1}_{FMS},\ E^{2}_{FMS},\ E^{3}_{FMS}\right\} \cup \{e_{FMS}\} , \tag{2.2}$$

where “e_{FMS}” represents the neutral event embedded in the monoid E^{*}_{dFMS}. Thus for $Sync_{FMS}$ the components are defined:

$$\begin{array}{l} Sync1_{FMS} : T_{35} \rightarrow \left\{E^{1}_{dFMS}\right\} \\ Sync2_{FMS} : T_{27} \rightarrow \left\{E^{2}_{dFMS}\right\} , \\ Sync3_{FMS} : T_{20} \rightarrow \left\{E^{3}_{dFMS}\right\} \end{array} \tag{2.3}$$

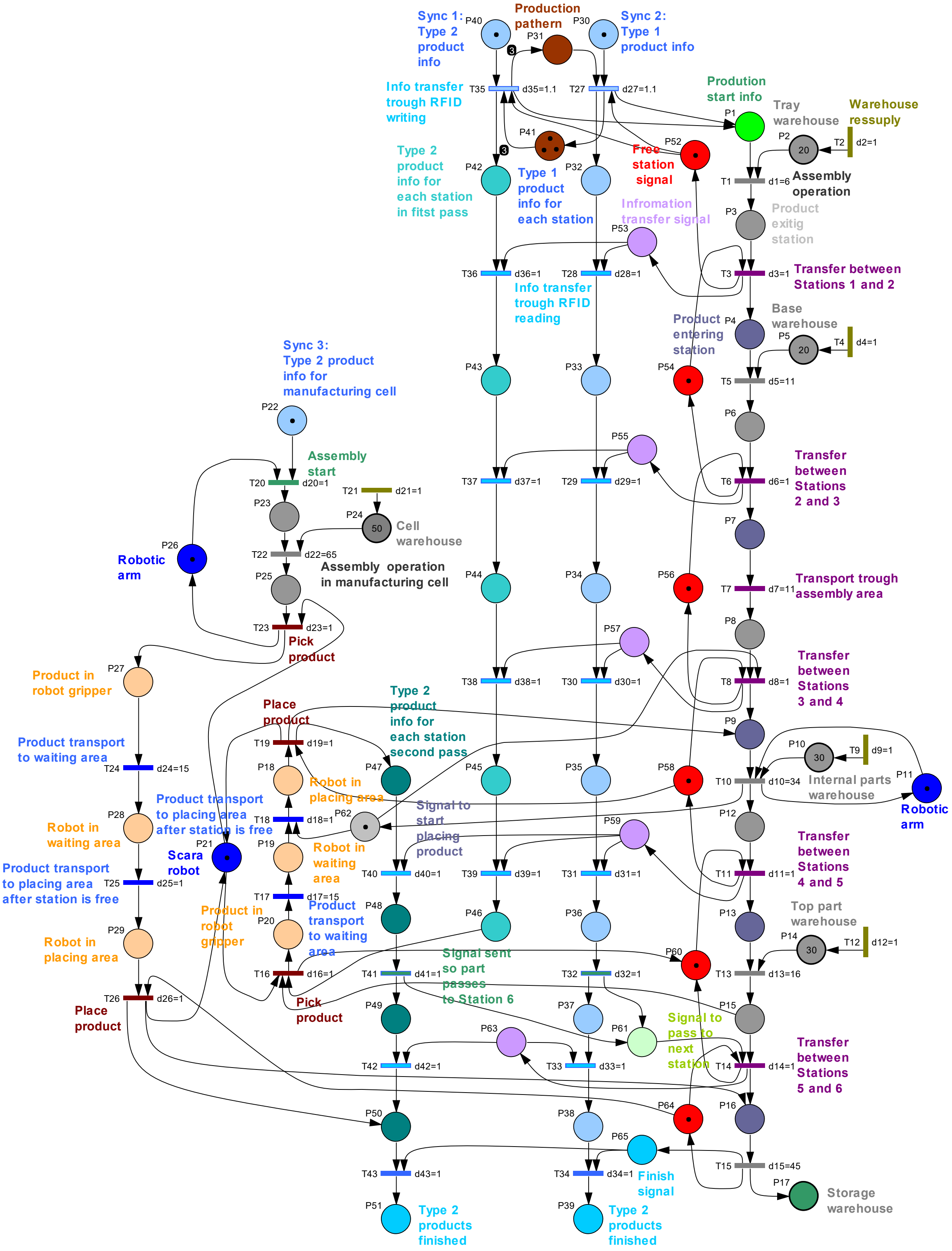


Figure 11. The RPS model associated with flexible manufacturing on a production system with two parallel flows

where:

$E^{1}_{dFMS} = Sync1_{FMS}$ - represents the synchronization signal used to transmit Type 2 product information from the manufacturing planning algorithm to the flexible manufacturing process in flow;

$E_{dFMS}^{2} = Sync2_{FMS}$ - represents the synchronization signal used to transmit information associated with the Type 1 product from the manufacturing planning algorithm to the flexible manufacturing process in flow;

$E_{dFMS}^{3} = Sync3_{FMS}$ - represents the timing signal used to transmit information associated with product Type, 1 from the manufacturing planning algorithm to the flexible manufacturing process in the cell.

The results of the simulation show the moment when the product, manufactured in FMC, arrives at Station 5, from where it will be picked up and transported to the quality control area. At the same time, the product manufactured on the FFM is stationed in the pick-up area of Station 5, giving priority access to the products on the parallel flow.

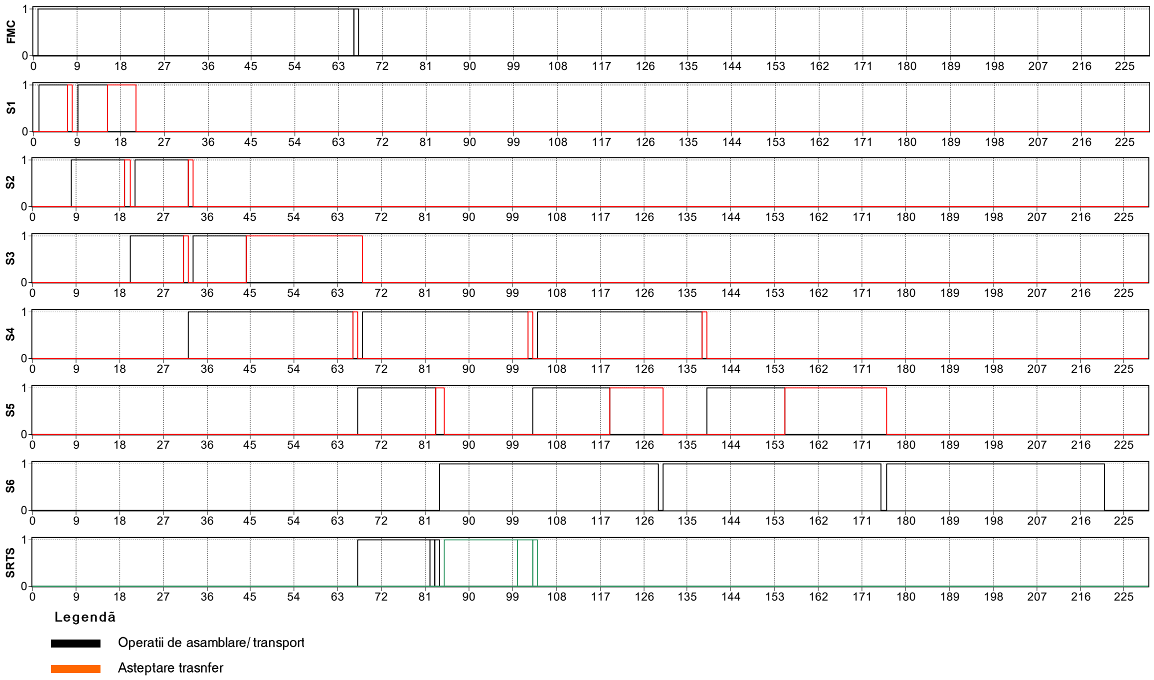


Figure 12. Simulation results of the RPT model associated with IFMS

The simulations evaluate the waiting times, synchronization of the operations carried out on the two parallel production flows and the occurrence of blockages. In the management of the process, for the stations located at the convergence of the two production flows, the priority restrictions are respected which are intended to avoid collisions, respectively blockages..

2.2. RPS Modelling of Flexible Manufacturing/Assembly Processes in stations

In the following subchapters, RPS models corresponding to each station will be presented, identifying the implications of the simulation results in the design and implementation of IFMS management.

2.2.1. RPS modelling of flexible manufacturing in Station 1

In Station 1 of the flexible manufacturing system, the product assembly process is initiated by placing a pallet equipped with an RFID tag on the transport system (Figure 23). The RFID tag ensures the recording, reading and transmission of technical data between stations, without the need for synchronized communication between them.

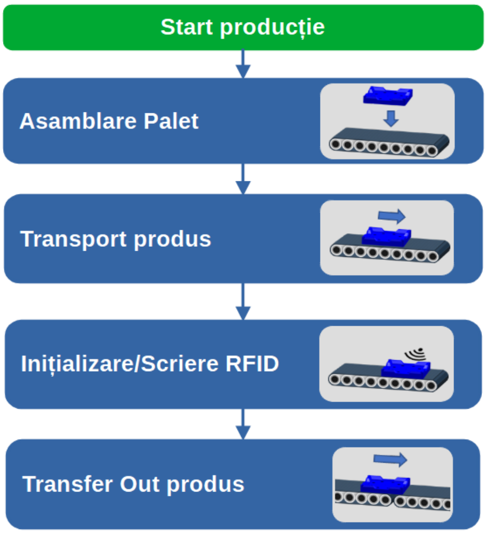


Figure 13. Block diagram of manufacturing operations in Station 1

Generic model of a workstation has specific typology of Synchronized Petri Net:

$$RPS_{S1} = \langle RPT_{S1},\ E_{dS1},\ Sync_{S1} \rangle\,, \tag{2.4}$$

The $Sync_{S1}$ function conditions the execution of some transitions on the reception of the external events with which they are synchronized:

$$Sync_{S1} : \{T_1,\ T_2,\ T_7\} \rightarrow \left\{E^1_{dS1},\ E^2_{dS1},\ E^3_{dS1}\right\} \cup \{e_{S1}\}\,, \tag{2.5}$$

where “e_{S1}” represents the neutral event embedded in the monoid E^*_{dS1}. Thus, for $Sync_{S1}$, the components are:

$$\begin{aligned} Sync1_{S1} &: T_1 \rightarrow \left\{E^1_{dS1}\right\} \\ Sync2_{S1} &: T_2 \rightarrow \left\{E^2_{dS1}\right\}\,, \\ Sync3_{S1} &: T_7 \rightarrow \left\{E^3_{dS1}\right\} \end{aligned} \tag{2.6}$$

where:

$E^1_{dS1} = Sync1_{S1}$	→ represents the signal for synchronizing assembly operations with the reception of production sequence planning information for Type 1 products;
$E^2_{dS1} = Sync2_{S1}$	→ represents the signal for synchronizing assembly operations with the signal for receiving production planning information for Type 2 products;
$E^3_{dS1} = Sync3_{S1}$	→ represents the product transport synchronization signal from Station 1 to Station 2 with the station availability status validation signal.

2.2.2. RPS modelling of flexible manufacturing in Station 2

In Station 2, the base component is placed on a pallet equipped with an RFID tag. This operation is common to all manufacturing operations. Figure 26 shows the sequence of tasks performed in Station 2, during the assembly process.

Similar to Station 1, the model of Station 2 can be expressed as:

$$RPS2 = \left\langle RPT_{S2},\ E_{dS2},\ Sync_{S2} \right\rangle \ . \tag{2.7}$$

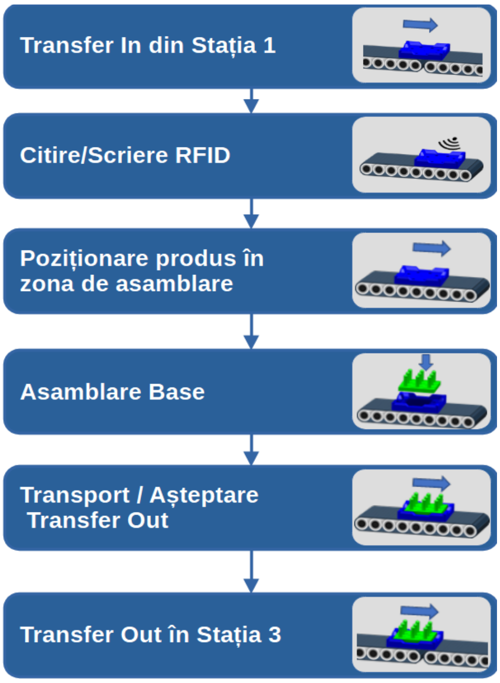


Figure 14. Block diagram of manufacturing operations in Station 2

the $Sync_{S2}$ associates certain transitions with external events:

$$Sync_{S2} : \{T_1,\ T_2\} \rightarrow \left\{E^1_{dS2},\ E^2_{dS2}\right\} \cup \{e_{S2}\}, \tag{2.8}$$

where “e_{S2}” represents the neutral event in the monoid E^*_{dS2}. Thus, they can be written:

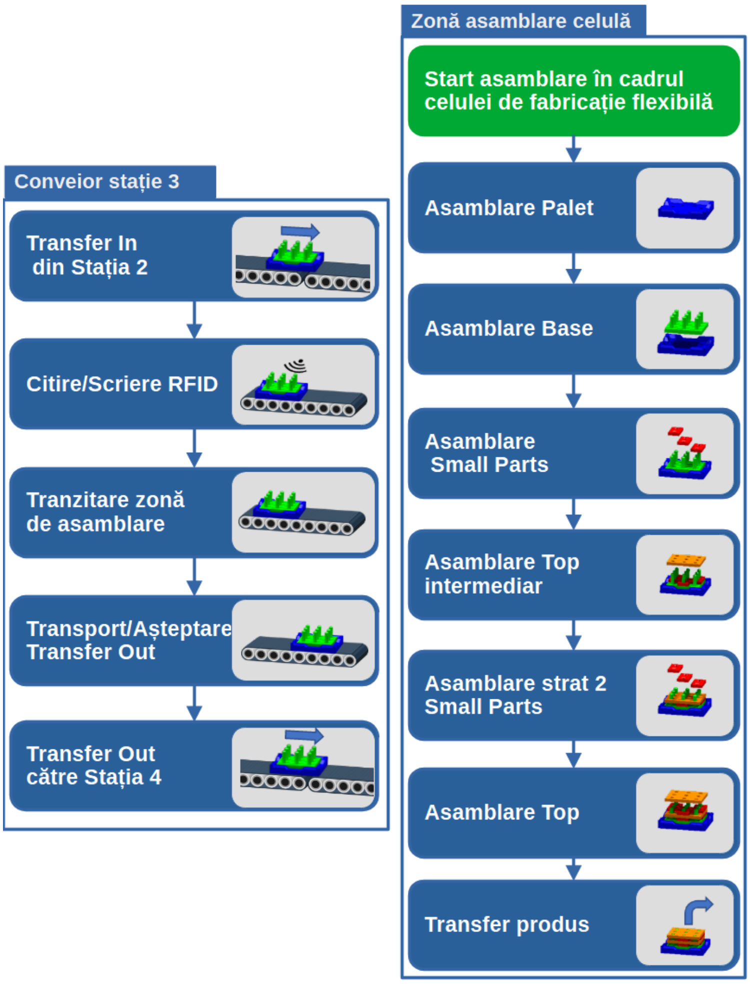
$$\begin{aligned} Sync1_{S2} &: T_1 \rightarrow \left\{E^1_{dS2}\right\} \\ Sync2_{S2} &: T_5 \rightarrow \left\{E^2_{dS2}\right\} \end{aligned} \ , \tag{2.9}$$

$E^1_{dS2} = Sync1_{S2}$ → represents the synchronization signal of the end of the assembly in Station 1, with the initiation of the transfer to Station 2. The event is conditional on the availability of Station 2;

$E^2_{dS2} = Sync2_{S2}$ → represents the synchronization signal of the end of assembly in Station 2, with the initiation of the transfer to Station 3. The event is conditional on the availability of Station 3.

2.2.3. RPS modelling of flexible manufacturing in Station 3

Production in Station 3 involves the execution of two parallel processes: flexible manufacturing in flow and flexible manufacturing in cell (Figure 29). The product being assembled through flow manufacturing will transit Station 3, without undergoing technological changes, and without stopping. Station 3 is dedicated exclusively to flexible manufacturing in the cell, where the operations are carried out by the ABB manipulator. For flexible in-cell manufacturing, multilayer product assembly was considered. Type 1 and Type 2 product, which respects production planning.



(a) (b)

Figure 15. a) Block diagram of operations related to flow manufacturing in Station 3; b) Block diagram of operations related to flexible manufacturing in the cell of Station 3

The modelling of the two parallel processes in Station 3 are integrated into a model with RPS:

$$RPS_{S3} = \langle RPT_{S3},\ E_{dS3},\ Sync_{S3} \rangle , \tag{2.10}$$

Considering the set of external signals, the function $Sync_{S3}$ is used to correlate the validation of some transitions, by the associated external signals, resulting:

$$Sync_{S3} : \{T_1,\ T_5,\ T_{15},\ T_{16}\} \rightarrow \left\{E^1_{dS3},\ E^2_{dS3},\ E^3_{dS3},\ E^4_{dS3}\right\} \cup \{e_{S3}\} \ , \tag{2.11}$$

where “e_{S3}” represents a neutral event within the monoid E^*_{dS3}. Thus, results

$$\begin{array}{l} Sync1_{S3} : T_1 \rightarrow \left\{E^1_{dS3}\right\} \\ Sync2_{S3} : T_5 \rightarrow \left\{E^2_{dS3}\right\} \\ Sync3_{S3} : T_{15} \rightarrow \left\{E^3_{dS3}\right\} \\ Sync4_{S3} : T_{16} \rightarrow \left\{E^4_{dS3}\right\} \end{array} , \tag{2.12}$$

$E_{dS1}^{1} = Sync1_{S3}$ → represents the signal for synchronizing the initiation of flexible manufacturing in flow, with the signal for validating the presence of a product, at the exit from the previous station;

$E_{dS1}^{2} = Sync2_{S1}$ → represents the synchronization of the start of the product transfer operation to the next station, with the signal to validate its availability;

$E_{dS3}^{3} = Sync3_{S3}$ → represents the synchronization of the start of the flexible manufacturing process in the cell with the transmission of production planning data;

$E_{dS3}^{4} = Sync4_{S3}$ → represents the synchronization of the completion of the assembly of a product in the flexible cell, with the signal to validate the availability of the SCARA transport system, to carry out the transfer of the product to the quality control point.

2.2.4. RPS modelling of flexible manufacturing in Station 4

In Station 4, which is served by the FANUC robotic manipulator, it is possible to assemble products with different configurations, according to the manufacturing range. They are structured on intermediate layers (Figure 32). The product launched in manufacturing has a pre-set configuration through the human-machine interface HMI, which allows the customization of the two types of products, which will be launched in production. Within this interface, the user can select the product type and component layer configuration. This data is transferred to the RFID tag in Station 1, and read in Station 4. Based on the selected configuration, the product is to be assembled.

The model associated with Station 4 is defined as an RPS type model:

$$RPS_{S4} = \langle RPT_{S4},\ E_{dS4},\ Sync_{S4} \rangle, \tag{2.13}$$

Considering the set of external signals, the function $Sync_{S4}$ is used to correlate a set of transitions, with the associated external signals:

$$Sync_{S4} : \{T_1,\ T_{16},\ T_{41}\} \rightarrow \left\{E_{dS4}^{1},\ E_{dS4}^{2},\ E_{dS4}^{3}\right\} \cup \{e_{S4}\}, \tag{2.14}$$

with “e_{S4}” a neutral event of the monoid E_{dS4}^{*}. The $Sync_{S4}$ synchronization function detailed by component is:

$$\begin{aligned} &Sync1_{S4} : T_1 \rightarrow \left\{E_{dS4}^{1}\right\} \\ &Sync2_{S4} : T_{16} \rightarrow \left\{E_{dS4}^{2}\right\}\ , \\ &Sync2_{S4} : T_{41} \rightarrow \left\{E_{dS4}^{3}\right\} \end{aligned} \tag{2.15}$$

$E_{dS4}^{1} = Sync1_{S4}$ → represents the synchronization signal of the initiation of the transfer operation from the previous station, with the check of the availability of the current station;

$E_{dS4}^{2} = Sync2_{S4}$ → represents the synchronization signal of the initiation of the transfer of the product to the next station, with the check of the availability status of the next station (free station);

$E_{dS4}^{3} = Sync3_{S4}$ → represents the synchronization signal for positioning the SCARA robot in the dedicated location for product transfer to the station, with the conveyor line stop signal, in view of its takeover.

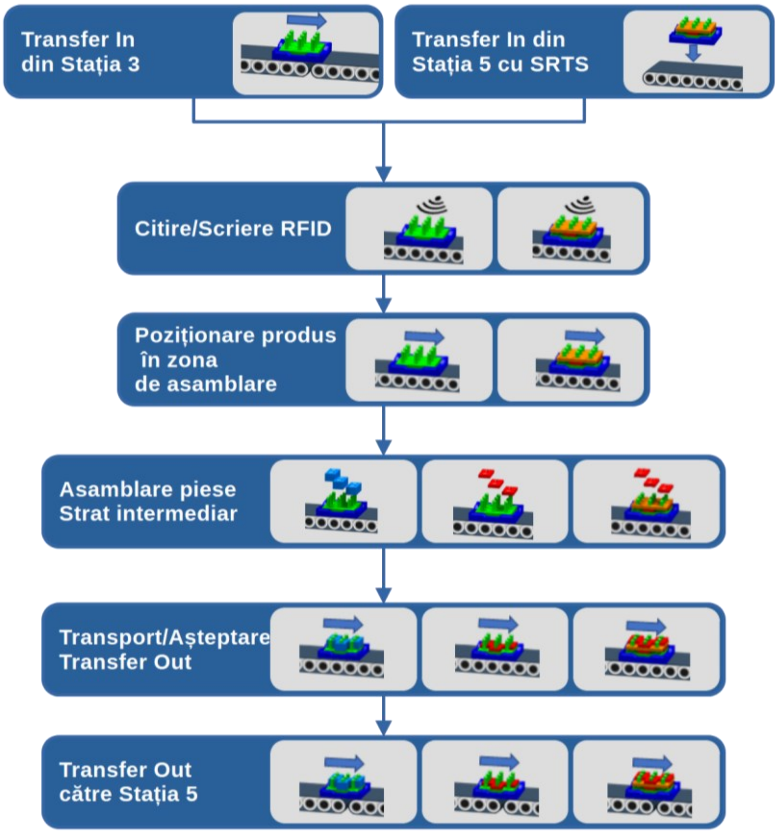


Figure 16. Block diagram of flexible manufacturing operations in Station 4

2.2.5. RPS modelling of flexible manufacturing in Station 5

Three work scenarios are possible in Station 5 (Figure 35):

- ✓ in the first scenario, the Type 2 part is subjected to assembly operations, top pressing, followed by the transfer of the finished product to the quality test.
- ✓ in the second scenario, the Type 1 part, located at the first pass, is subjected to the cover assembly operation, followed by its transfer back to Station 4. The handling (pick-up and dropping) and transport operations are carried out by the SCARA robotic transport system . The operation of transferring the product to the station is synchronized with the transport stop signal on the manufacturing line;
- ✓ in the third scenario, the Type 1 part, for which the assembly operation of the second intermediate layer has been completed, is subjected to the final assembly operations, top pressing, followed by the transfer of the finished product to the quality test..

The RP model associated with Station 5 has the RPS typology and is defined as such:

$$RPS_{S5} = \langle RPT_{S5},\ E_{dS5},\ Sync_{S5} \rangle, \qquad (2.16)$$

The $Sync_{S5}$ function defines the associations between a set of transitions and a set of external events, represented by:

$$Sync_{S5} : \{T_1,\ T_6,\ T_7,\ T_9\} \rightarrow \left\{E_{dS5}^{1},\ E_{dS5}^{2},\ E_{dS5}^{3},\ E_{dS5}^{4}\right\} \cup \{e_{S5}\}\ , \qquad (2.17)$$

With the components:

$$\begin{array}{l} Sync1_{S5} : T_1 \rightarrow \left\{ E_{dS5}^{1} \right\} \\ Sync2_{S5} : T_6 \rightarrow \left\{ E_{dS5}^{2} \right\} \\ Sync3_{S5} : T_7 \rightarrow \left\{ E_{dS5}^{3} \right\} \\ Sync4_{S5} : T_9 \rightarrow \left\{ E_{dS5}^{4} \right\} \end{array}, \qquad (2.18)$$

$E_{dS5}^{1} = Sync1_{S5}$ → represents the synchronization signal of the initiation of the transfer of the product from the previous station, with the current station's availability validation signal;

$E_{dS5}^{2} = Sync2_{S5}$ → represents the synchronization signal of the initiation of the transfer of the product from the current station, with the signal of validation of the availability of the next station;

$E_{dS5}^{3} = Sync3_{S5}$ → represents the synchronization signal of the initiation of the transport of the assembled product in Station 3 with the signal that checks the availability of the waiting area in Station 5;

$E_{dS5}^{4} = Sync4_{S5}$ → represents the synchronization signal of the initiation of the transfer of the Type 1 part, with the signal that checks the availability of Station 4 for the cyclic resumption of the assembly operations of a new layer.

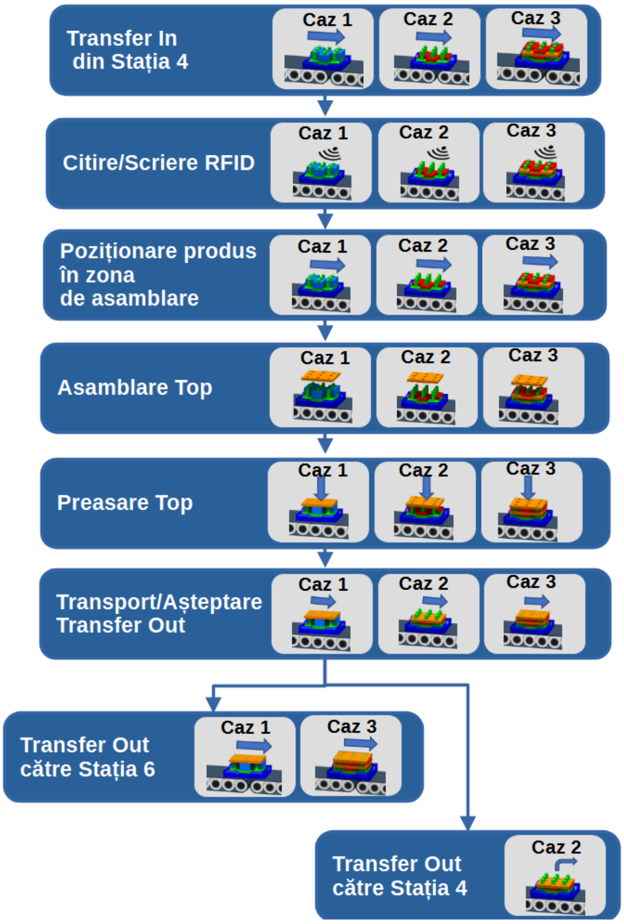


Figure 17. Block diagram of flexible manufacturing operations in Station 5

2.2.6. RPS modelling of flexible manufacturing in Station 6

Station 6 is specialized in performing the product quality test, followed by and storing the compliant products in the dedicated warehouse (Figure 38). If a product does not meet the required quality standards, it will be subject to disassembly.

The model associated with Station 6 has the RPS typology and is defined as such:

$$RPS_{S6} = \langle RPT_{S6},\ E_{dS6},\ Sync_{S6} \rangle . \tag{2.19}$$

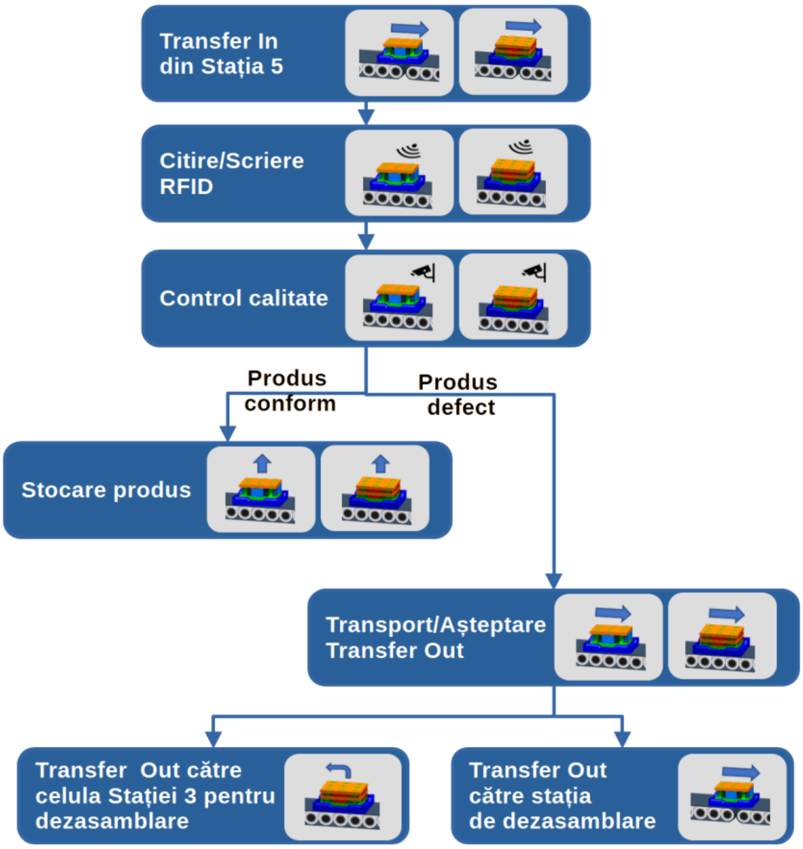


Figure 18. Block diagram of manufacturing operations in Station 6

The function $Sync_{S6}$ represents the associations between the set of transitions and the set of external events, defined by

$$Sync_{S6} : \{T_1,\ T_6,\ T_8\} \rightarrow \left\{E^1_{dS6},\ E^2_{dS6},\ E^3_{dS6}\right\} \cup \{e_{S6}\}, \tag{2.20}$$

of which they are components:

$$\begin{aligned} Sync1_{S6} &: T_1 \rightarrow \left\{E^1_{dS6}\right\} \\ Sync2_{S6} &: T_6 \rightarrow \left\{E^2_{dS6}\right\} \ , \\ Sync3_{S6} &: T_8 \rightarrow \left\{E^3_{dS6}\right\} \end{aligned} \tag{2.21}$$

$E^1_{dS6} = Sync1_{S6}$ → represents the synchronization signal of the initiation of the product transfer from the previous station with the location availability validation signal in the current station;

$E_{dS6}^{2} = Sync2_{S6}$ → represents the synchronization signal of the initiation of the transfer of the product from the current station, with the signal of validation of the availability of the next station;

$E_{dS6}^{3} = Sync3_{S6}$ → represents the synchronization signal for initiating the transfer of the defective product to Station 3, with the signal for validating the availability of Station 3 for disassembly.

2.3. Scientific results and contributions

Following the RPS modelling of the control of the integrated system with two parallel production flows, namely flexible flow manufacturing and flexible cell manufacturing, RPS models were obtained. By simulating the RPS models, data is obtained that is the basis for the implementation of the real-time management of the IFMS, with the application of the Digital twin concept. RPS models were made for each station, which allowed the modelling of sequential operations, at the local level, but also of task synchronizations with parallel execution, for functionally interconnected systems.

> In this section, the subordinate objectives of OB.2, regarding the modelling of the dynamics of the flexible manufacturing process, with the integration of Industry 4.0 and 5.0 concepts, with an emphasis on IoE and Digital twin, respectively OB.2.1, were achieved. Timed Petri Nets (RPT) modelling of the control of the integrated system with two parallel production flows: flexible manufacturing on the line and flexible manufacturing in the cell, with the application of the Digital twin concept and OB.2.3. Synchronized Petri Nets (RPS) modelling of station-level control of flexible manufacturing and process data reading and processing structure, applying the Digital twin concept.
>
> The use of RPS models allowed the assessment of conditioning and synchronization between processes, the identification of critical situations, aspects regarding possible improvements in production performance. The implementation of process control and robotic systems will be based on the interfacing and synchronization of the simulation of digital RPS models, with the real-time control of the processes, through the application of Digital twin.
>
> The implementation of management at the workstation level, coordinated with RPS models, represents an important scientific contribution, with implications in reducing waiting times, implicitly the production cycle time.
>
> The presented approach pursued an educational goal, as well as an advanced research for the design and modelling of processes, as integrated structures in the real world, in the sense of manufacturing and environmental sustainability. The educational goal will familiarize the system designer with the concept of Industry 5.0 - Education 5.0, as well as with specific Cyber-Physical-System aspects, in the sense of the convergence between hardware and cyber resources. The educational aspect is enhanced by the use of advanced tools in modelling, namely RPS. Research highlights RPS modelling of signal synchronizations acquired from sensors and actuators, as well as modelling of task synchronizations generated by the monitoring system. RPS models will be useful in implementing real-time control with Digital twin technology.

Chapter 3

Automatic management of transport operations and precise positioning in ISFM stations, subject to the concepts of Industry 4.0 and 5.0

Since the design of the integrated system for flexible manufacturing has resulted in a system with two parallel manufacturing flows, it is important to precisely coordinate the operations of positioning parts in key locations at certain points in time. This approach was anticipated by the RPS modelling of each workstation, where the use of timing events indicates the temporal and precise positioning of a product in execution at that workstation.

If we refer generically to a workstation, the position of a product is measured at three key locations using binary detection sensors (Figure 41). The position of a product, on the conveyor, is measured at the entrance to the station, at the exit and in the work area of the station. By hypothesis, at a given moment, only one product is present on the conveyor. In classical in-station transport control programming, a series of events are initiated upon sequential activation of sensors.

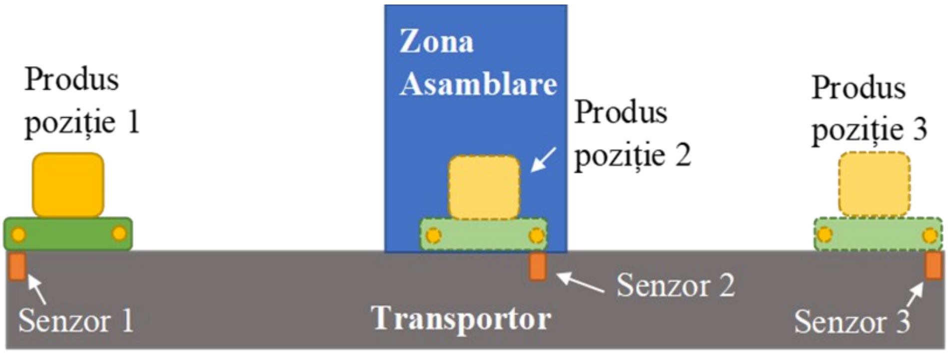


Figure 19. Positioning sensors in a workstation

The control algorithm will consider certain limitations:

- ✓ in a manufacturing process, transport follows the direction of conveyors and their direction, so the product cannot travel back to a location.
- ✓ the transport system has certain limits, generated by the speed of the conveyor belts, which requires the design of the conveyor speed control structure - the order size, within the working limits of the physical system.

Thus, in managing the transport process, it is proposed to implement a management structure that ensures movement on the conveyor, within a predetermined time interval, respecting the minimum and maximum values of the order. The use of the PID algorithm was chosen.

3.1. Control structure with PID algorithm

PID controllers are the most used industrially, in automation applications. Through the three components, proportional, integrative, derivative, the PID structure elaborates the process command, respecting the performances imposed on the controlled quantity..

The input ($E(s)$) / output ($U(s)$) equation of the PID controller in standard form, in the complex domain s, is [87, 88]:

$$U(s) = K_R [E(s) + \frac{1}{T_I s} \cdot E(s) + T_D \cdot s \cdot E(s)] , \tag{3.1}$$

In the case of a real process, the commands transmitted by the control system must fall within the allowable limits of the execution elements. Thus, to ensure an optimal correlation between the controller and the physical limitations of the system, a set of command saturation rules is proposed

$$\begin{cases} U_{Command}(s) = U_{Inferior} & , \text{dacă} \;\; U(s) < U_{Inferior} \\ U_{Command}(s) = U(s) & , \text{dacă} \;\; U_{Inferior} \le U(s) \le U_{Superior} \\ U_{Command}(s) = U_{Superior} & , \text{dacă} \;\; U(s) > U_{Superior} \end{cases} . \tag{3.2}$$

If saturation rules are implemented, there is a risk that the integrator factor in the PID controller will introduce delays and generate unwanted oscillations in the response. To prevent this, anti-windup methods are proposed.

3.2. A Event-based PID control algorithm

The research published in the specialized literature regarding event-based PID controllers (PID_E) - PID event triggers, propose the implementation of an event-type regulation law based on input quantities. It is proposed to use two distinct systems: an acquisition device that detects the event, and a PID controller that elaborates the command based on the detected event. The controller develops a new command at each detected event, and this command acts with constant value, until the next event is detected.

Similar to the time-sampling PID controller, the event detector measures at predetermined time intervals the value of the controlled quantity, starting from a sampling period $\bar{h}$. In the literature, the triggering event is often defined as the absolute value of the error, $e(t_k)$ that exceeds a predefined level $\bar{e}$. Thus, the condition for associating the error value with an event is defined by the following inequality [95]:

$$\left|e(t_k)\right| \ge \bar{e}, \tag{3.3}$$

where $t_k = \sum_k h_k$ represents the time instants generated by sampling with $h_k = t_k - t_{k-1}$.

3.3. Control design with PID_E algorithm for transport and positioning, in workstations

In the process of designing an efficient control algorithm, for a station equipped with a conveyor, it was necessary to identify the transfer function associated with the conveyor transport process. For this, specialized utilities of the Matlab software, **PID Tuner_Plant**

Identification, were used. After identifying the process model, respectively the transfer function, the transport on the conveyor belt was simulated (Figure 42.a). The simulation results were correlated with real-time monitoring of input and output quantities from the conveyor system.

The experimental data vectors were retrieved in the **Matlab PID Tuner_Plant Identification** software utility. Through processing techniques provided by the *Plant Identification* utility, the transfer function that approximates the dynamics of the process was obtained:

$$H(s) = \frac{1.3}{0.1s^2 + s} \tag{3.4}$$

In order to compensate for these errors, a control structure with a PID_E controller was implemented. In the response analysis, order perturbations were taken into account - additive perturbations on the input as well as on the output magnitude. In the control structure of the conveyor system (Figure 44), it was found that the control disturbances are caused by the control circuits of the conveyor motors, which work only with integer values. Additive disturbances on the output (product position on the conveyor), are caused by the measurement errors of the sensors.

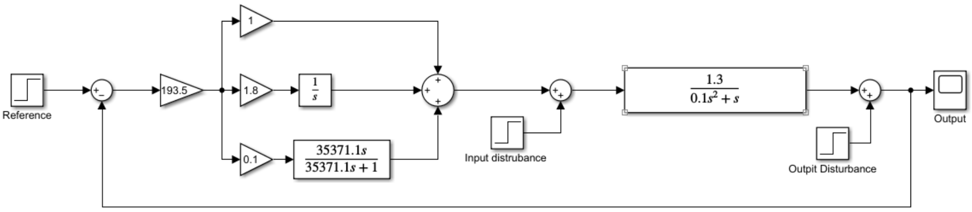


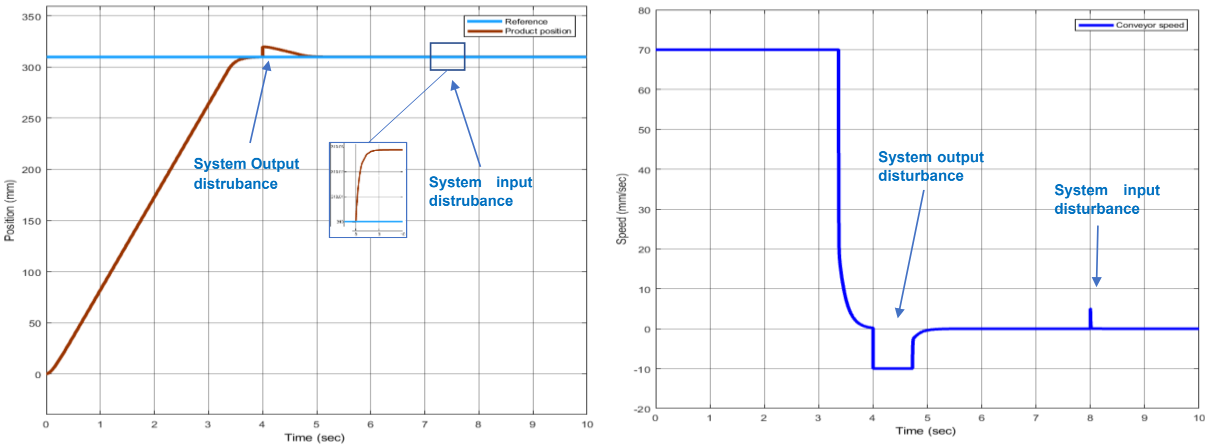
Figure 20. Simulink model corresponding to the PID control structure under the action of disturbances

For the two management structures, they were evaluated by simulation:

- ✓ the output size of the process (position on the conveyor) in the absence of disturbances – i.e. tracking the unit step reference (*Step plot: Reference tracking*)
- ✓ the output size of the process (position on the conveyor) if disturbing signals are considered unitary step, applied additively per order (*Step plot: Input disturbance rejection*)
- ✓ the output size of the process (position on the conveyor) if only single step disturbances applied additively on the output are considered, respectively the position on the conveyor (*Step plot: Output disturbance rejection*).

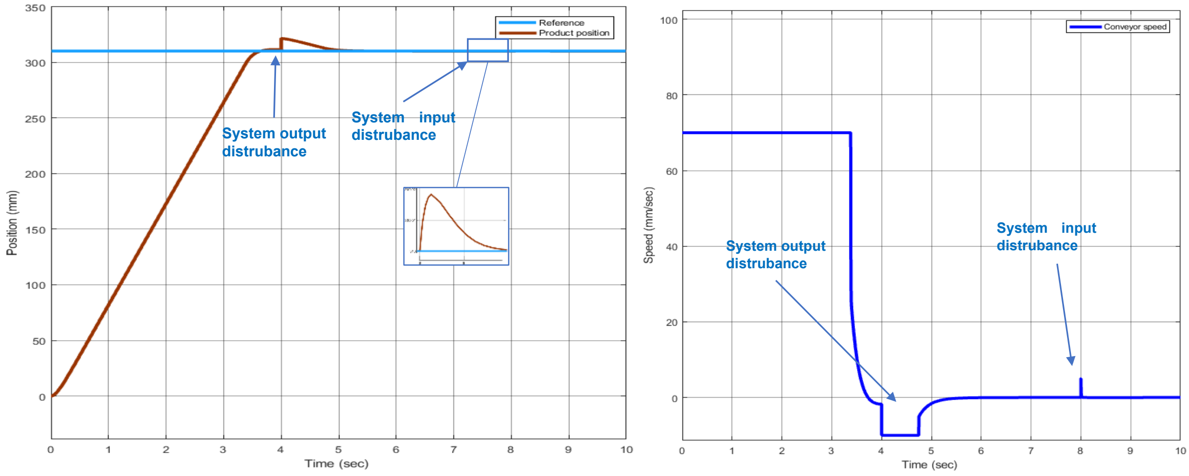
In the two cases, comparable performance of the response is obtained, in the absence of disturbances (*Reference tracking*). The notable differences between the two control structures are of the output magnitude, relative to the disturbance rejection action, applied additively to the input and output of the system. In the case of compensating the disturbances applied to the output, the closed-loop regulation structure with unitary negative feedback and PID controller ensures good performance, with very low disturbance attenuation time.

In Figure 47 and Figure 48, the results of control simulation, with PD and PID controllers, are presented for the operations: conveyor transport, respectively precision positioning.



a) b)

Figure 21. Results of the PD control simulation of the transport and positioning process, under the action of disturbances: a) Positioning in relation to the reference and; b) the transport speed of the conveyor belt



a) b)

Figure 22. Results of the PID control simulation of the transport and positioning process, under the action of disturbances: a) Positioning in relation to the reference and; b) the transport speed of the conveyor belt

Following the comparative evaluation of the response performances for the two control structures, the following judgments can be made: the action of the PID controller leads to superior performance in terms of rejecting the disturbances applied to the input and ensures zero position error

Algorithm 1 proposes to replace the fault level based trigger with a new product position based trigger

PID_E algorithm: Algorithm for event-based PID control

```
Intrări:  y_ref //poziția de referință
          y //poziția produsului
          // evenimentul de activare determinat de senzori
          actv=  1, dacă unul dintre senzori este activ
                 0, în caz contrar
Ieșiri: u_com //viteza transportorului
//Calcularea timpului între activări: t_pres = t_pres + t_nom
if (actv = 1)
```

```
    er = y_ref – y
    up = K * (beta * y_ref – y)
    ud = Td/(N * t_pres + Td) * ud_old – K * Td * N/(N * t_pres + Td) * (y – y_old)
    ui = ui_old + K/Ti – t_pres * e
    u = up + ui + ud
//saturarea și anti-windup
    if (u < u_inferior) then //valoarea comenzi sub o anumită limită
        u_com = u_inferior
        ui = ui_old
    else if (u > u_superior) then //valoarea comenzii peste o anumită limită
          u_com = u_superior
          ui = ui_old
        else
          u_com = u
          ui = ui_old + K/Ti – t_pres * e
        end
    end
//modificarea valorilor
    ui_old =ui
    ud_old =ud
    y_old = y
    t_pres = 0 //resetarea timpului
End
```

3.4. Implementation of PID_E control of transport and precise positioning operations

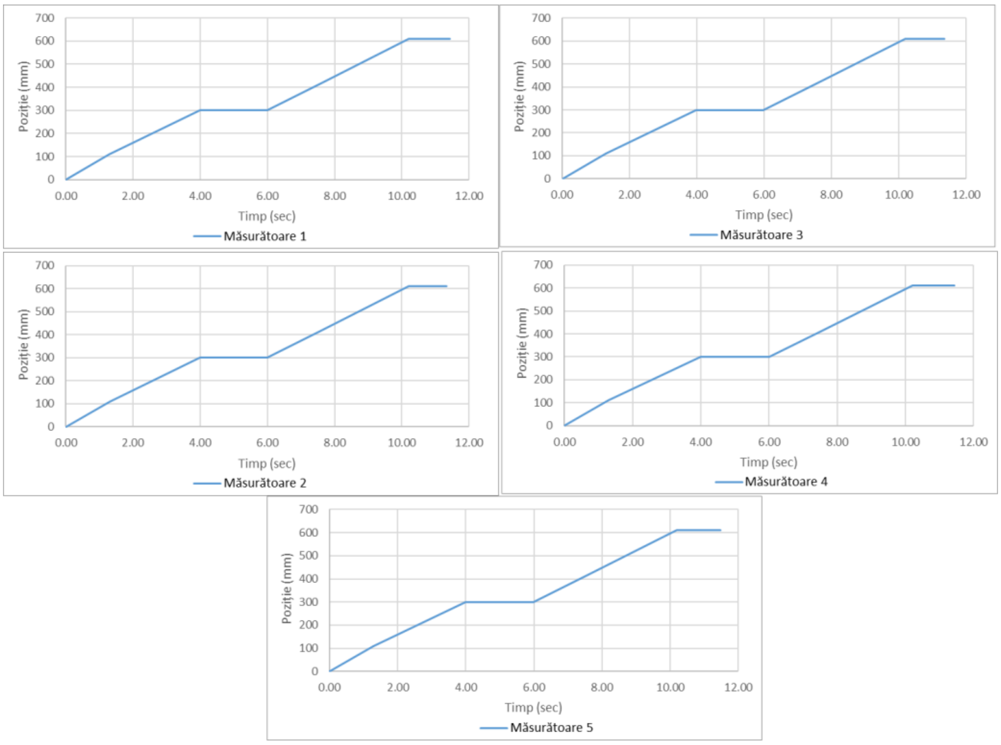


Figure 23. Monitoring successive positions for control with Algorithm PID_E

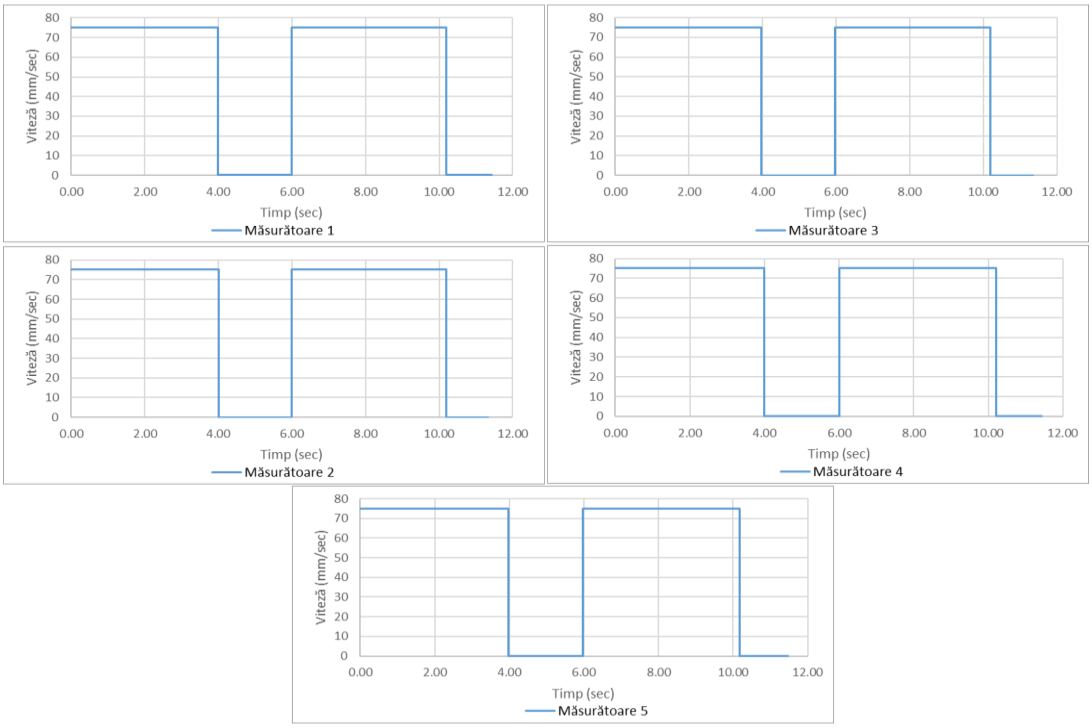


Figure 24. Command monitoring for control with Algorithm PID_E

Figure 51 and Figure 52 show the results of monitoring the command values, delivered by the product control and positioning algorithm, obtained by implementing the **PID_E Algorithm**. A set of five measurements was performed to determine the repeatability of the values and to identify possible disturbances. These measurements were based on the PID algorithm control structure with previously determined parameters

When applying **PID_E Algorithm** control, optimal response performance is obtained, with command value saturation leading to performance close to that of conventional PID control. Regarding the order size values, the analysis carried out reveals the repeatability of the process sizes, with variation below 0.5%. This variation is compensated so that it does not significantly affect the output value, respectively the positioning value of the product.

3.5. Scientific results and contributions

In this chapter we detailed the design and implementation of a structure for managing the transport operations and precision positioning of parts in the work station, for each of the IFSM stations. The approach considered the presence of additive perturbations on the order and on the process output quantity, namely the positioning error measured relative to a preset reference. In a first step, by using a specialized Matlab software application, PID Tuner_Plant Identification, the mathematical model of the process, respectively the transfer function, was identified. Through repeated simulations of the model in Simulink, corresponding to the control structure with PID, in which the action of additive disturbances on the input and output of the process is considered, the performance of the control structure was evaluated, for values of the controller parameters, determined with PID_Tuner.

> In this section, the specific objectives of the general objective **OB.3**, regarding the management of transport operations and precise positioning of parts at the work point, for each of the IFMS stations, with the integration of the concepts of Industries 4.0 and 5.0, were achieved. PID_E algorithm control represents a significant scientific

contribution, which we propose in the area of manufacturing process control, where the monitoring of some process quantities is conditioned by the number and type of sensors installed in the stations.

The proposed integrated system for flexible manufacturing has the consistency of a CPS connected to concepts and technologies specific to Industries 4.0 and 5.0. Analysing the results of the research, at this moment of the report, concepts can be highlighted that represented important stages in the progress of the research, respectively in the conception, modelling and implementation of the hardware and management structure: ● CPS - implementation of an integrated system for flexible manufacturing with parallel production flows , fully automated, equipped with communication technologies in a hierarchical structure, which places it in the CPS class; ● Process robustness - the management structure of the IFSM gives the process the attribute of robustness. The process preserves its performances under the conditions of the action of the disturbing exogenous, thanks to the management structure with the rejection of disturbances; ● Production sustainability - work structure with switching to alternative flows, in case of failure of the current flow; ● Environmental sustainability - designing a sustainable system oriented towards total manufacturing subordinate to a complete operational cycle of production/recovery/reuse of components; ● Education 5.0 - advanced integrated system modelling for flexible manufacturing: RPT modelling of interconnected subsystems and processes; modelling with RPS the synchronized control of tasks; modelling with specialized RPS type tools of task synchronizations through process signal acquisitions.

Chapter 4

Optimal scheduling of flexible manufacturing with parallel flows

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The optimal planning problem is the natural consequence of approaching the general production volume distribution planning problem for parallel flow manufacturing. In general, optimal planning of manufacturing on multiple flows determines the distribution of production volumes on parallel subsystems, but also the balanced use of resources. Thus, the occurrence of blockages is avoided, and production efficiency and performance are maximized, which, in the approaches of Industries 4.0 and 5.0, corresponds to a high level of resilience and robustness of the industrial process.

In a general approach, ISFM is composed of workstations, interconnected or independent, resulting in two production subsystems:

- ✓ line for flexible flow manufacturing (FFM), with sequentially interconnected workstations;
- ✓ flexible manufacturing cell (FMC) served by a robotic manipulator and equipped with its own component warehouses, which is assimilated to an independent production system.

4.1. Algorithm Design for Optimal Scheduling of Flexible Manufacturing with Two Parallel Flows

In accordance with what has been presented and considering a hybrid production request, in the sense of the typologies, the problem arises of designing an algorithm for optimal planning of simultaneous manufacturing on FFM and FMC, based on the observance of task synchronizations, the distribution of production volumes on flows, reducing delays, minimizing total production time and balancing the use of ISFM resources.

4.1.1. One-station flow manufacturing analysis of FFM. Determination of characteristic values

Within a system for flexible manufacturing, the general structural and functional model of a station k is considered, with $k \in [1, N]$, and N the number of stations of the assembly line (Figure 53). Relative to a volume of products with the same typology, we consider a product p, where $p \in [1, P]$, P represents the entire volume of products.

$T_{prodmax}$ gives the work rate in the proecss, implicitly causes a bottleneck effect in the manufacturing process, as all other stations go into standby.

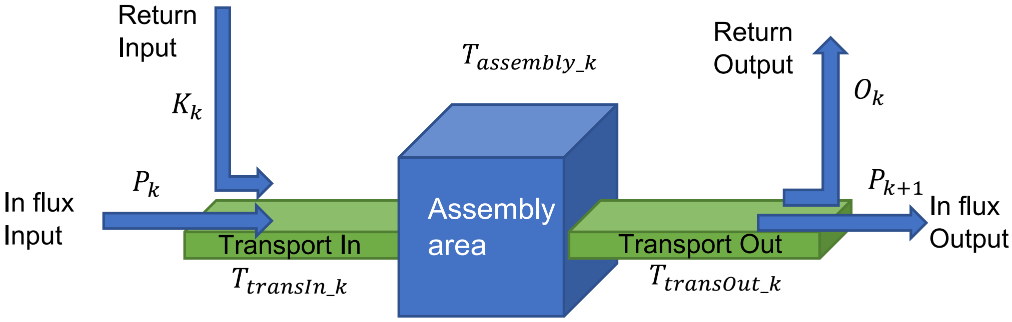


Figure 25. The sequence of transport and assembly operations in station k

Since all stations are synchronized with the station that has the maximum processing period, it is proposed to standardize the significance of the production time in station k as

$$T_{prod_k} = T_{prod\ max} \, . \tag{4.1}$$

Based on the significance of the production time T_{prod_k} and the sequence of operations, $T_{cycle_p^N}$ will be defined as the time required for the complete assembly of a product, i.e. the duration of a production cycle for an FFM manufactured product, with the relation:

$$T_{cycle_p^N} = \sum_{k=1}^{N} \sigma_{k,p}\ T_{prod_k} + \gamma_p T_{transport} + \sum_{k=1}^{N} T_{stop_{k,p}} \, , \tag{4.2}$$

4.1.2. Analysis of parallel manufacturing on FFM and FMC flows

For the representation of a general flexible manufacturing process (Figure 54) the manufacturing of a volume of Type 1 products was considered as being carried out by distributed tasks with parallel execution, on FFM and FMC. In this way, the optimal distribution will be determined, in the sense of the optimal planning of the simultaneous manufacturing, on the parallel flows.

They propose to determine the production time in FMC according to the following notations and working assumptions:

✓ $T_{prodcell}$ represents the manufacturing time of a Type 1 product, for FMC.
A workstation-equivalent approach is proposed for FMC:

$$T_{prodcell} = \beta\ T_{prod\,max}, \beta \in N^*, \beta \geq 1 \tag{4.3}$$

- $T_{transport}$ represents the duration of any transport sequence on the two processes, respectively the transport duration with SRTS.

Thus, for simplification, it is proposed to define the transport time as:

$$T_{transport} = \lambda T_{prod\,max}, \quad \lambda \in N, \quad \lambda \geq 1 \tag{4.4}$$

Applying these considerations and relations (4.4), (4.10) and (4.12) , the production cycle time on the FMC can be defined:

$$T_{CycleCell} = T_{prodcell} + T_{transport} + T_{prod_N}, \tag{4.5}$$

resulting:

$$T_{CycleCell} = (\beta + \lambda + 1) T_{prod\,max}. \tag{4.6}$$

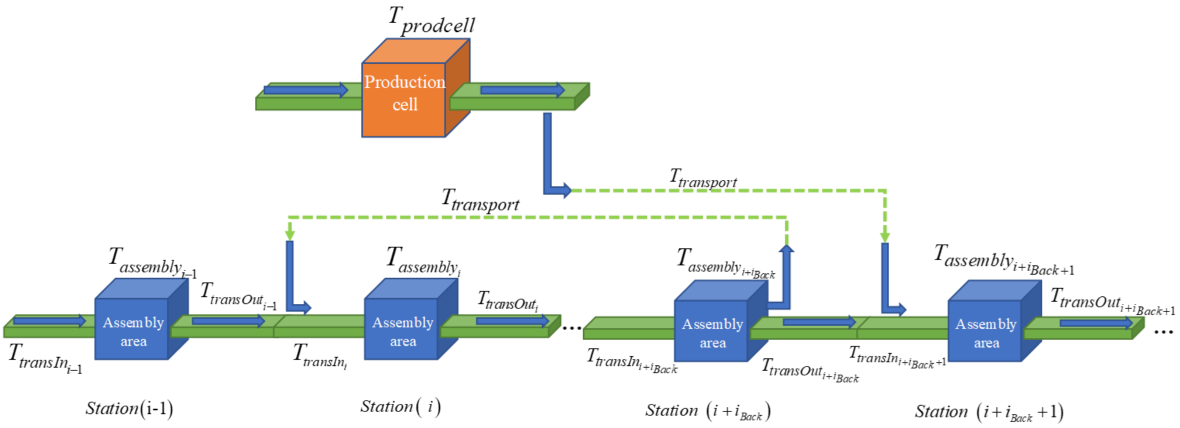


Figure 26. Succession of transport and assembly operations, for flexible manufacturing on parallel flows, FFM and FMC

4.2. Algorithm for optimal planning of parallel manufacturing, on FFM and FMC flows

According to the initial assumptions (respectively Ip.0.1. the Type 1 product can be executed on FFM and FMC; Ip.0.2. the Type 2 product is executed exclusively on FFM), the planning of production volumes assumes the optimal distribution, depending on the typology of the launched products in execution.

Thus, for product T_1, relations (4.5; 4.6; 4.12) are updated with the following variables:

$$T_{cycle_p^N} = \sum_{k=1}^{N} \sigma_{k,p} \, T_{prod_k} + \gamma_p T_{transport} + \sum_{k=1}^{N} T_{stop_{k,p}}, \tag{4.7}$$

For the production process on ISFM, the variables are defined υ_1 and υ_2 as the volume of products T_1 and T_2, taken from the customer by the production order.

Given the production volume υ_1 entered into the FFM flow, the total waiting time $T_{TotalWait}$ is calculated as

$$T_{TotalWait} = \sum_{T_2=1}^{\upsilon_2} \sum_{k=1}^{N} \theta_{k+1,T_2} T_{prod_{k+1}} + \sum_{T_1=1}^{\eta} \sum_{k=1}^{N} \theta_{k+1,T_1} T_{prod_{k+1}}. \tag{4.8}$$

The total waiting time for a simple production schedule can be expressed by

$$T_{TotalWait} = \upsilon_1 T_{prod\,max} \big|_{unoptimized}. \tag{4.9}$$

In the calculation of $T_{TotalWait}$ it was considered that the manufacture of the volume of products of T_1, introduces for each product, a waiting time equal to the production time of the station where it is introduced. Starting from relation (4.7) and RPS models of the manufacturing system, it can be concluded that when the products of $T_1$are taken by SRTS from FFM and returned with STRS for new operations, the products from FMC will be entered on FFM, without introducing waiting times. Thus, the total waiting time introduced by products from FMC on FFM will be zero (OB.4.1.4).

Considering this reasoning, the total waiting time can be defined as

$$T_{TotalWait} = (\upsilon_1 - \eta)\ T_{prod\,max}\,|_{optimized}\,. \tag{4.10}$$

In this sense, an optimization function is defined:

$$J_{IFMS} = min(T_{TotalWait})\,, \tag{4.11}$$

respecting the restriction of balanced distribution of production volumes on the two parallel flows FFM and FMC. This restriction was expressed through the relationship:

$$\sum_{r=1}^{\upsilon_1-\eta} T_{CycleCell} - T_{prodFFM} \simeq 0\,. \tag{4.12}$$

Through calculations:

$$\eta = \frac{\upsilon_1(\beta+1) - \upsilon_2 - N + 1}{\beta+3}\,, \tag{4.13}$$

which represents the volume of products of T_1, for manufacturing on FFM.

The implementation of relation (4.22) assumes the synchronization T_{sync} between production on FMC and production on FFM, with c - synchronization factor. Thus, if the transport between the two parallel flows respects the temporal constraints, it follows

$$T_{sync} = c\ T_{prod\,max}\,. \tag{4.14}$$

Using relations (4.5) and (4.29) in relation (4.31) we obtain

$$c = \beta + 1 - \left(i + i_{Back} + \theta_{i,T_1}\right). \tag{4.15}$$

By analysing the relation (4.32), three cases result:

$c<0$	production of product T_1 on FFM starts a period $\lvert c\rvert \cdot T_{prod\,max}$ before production on FMC begins;
$c=0$	production on the FFM and FMC flows starts simultaneously;
$c>0$	production of Type 1 products on FFM starts with a delay of $\lvert c\rvert \cdot T_{prod\,max}$ from the start time of production on FMC .

To verify the manufacturing efficiency on ISFM, two scenarios, namely two repetitive sequences of mixed manufacturing, provided by the optimal production planning algorithm, are proposed. Each repeating sequence contains a set of information relative to the number of parts and the product type ($T_1,\ T_2$). The manufacturing of the two product volumes results from hybrid manufacturing planning on the parallel production systems, FFM and FMC:

- *Scenario 1*

For $c \leq 0$ *the optimal planning algorithm provides the following manufacturing strategy on the two parallel flows:*

$$\begin{array}{ll} 1 & \text{produs Tip 1 pe fluxul FFM} \\ c & \text{produse Tip 2 pe fluxul FFM} \\ 1 & \text{produs Tip 1 pe fluxul FMC} \\ \beta - 2 - c & \text{produse Tip 2 pe fluxul FFM} \end{array}, \tag{4.16}$$

- *Scenario 2*

For $c > 0$ *the optimal planning algorithm provides the following manufacturing strategy on the two parallel flows:*

$$\begin{array}{ll} 1 & \text{produs Tip1 pe fluxul FMC} \\ c & \text{produse Tip 2 pe fluxul FFM} \\ 1 & \text{produs Tip1 pe fluxul FFM} \\ \beta - 2 - c & \text{produse Tip 2 pe fluxul FFM} \end{array}. \tag{4.17}$$

4.3. Scientific results and contributions

In this chapter, the research focused on the fulfilment of **OB.4**. *Optimal hybrid manufacturing planning, on a line for flexible manufacturing with two parallel production flows*. Thus, a general algorithm for optimal manufacturing planning was developed, which can be customized according to the hardware structure of the production system, with parallel flows.

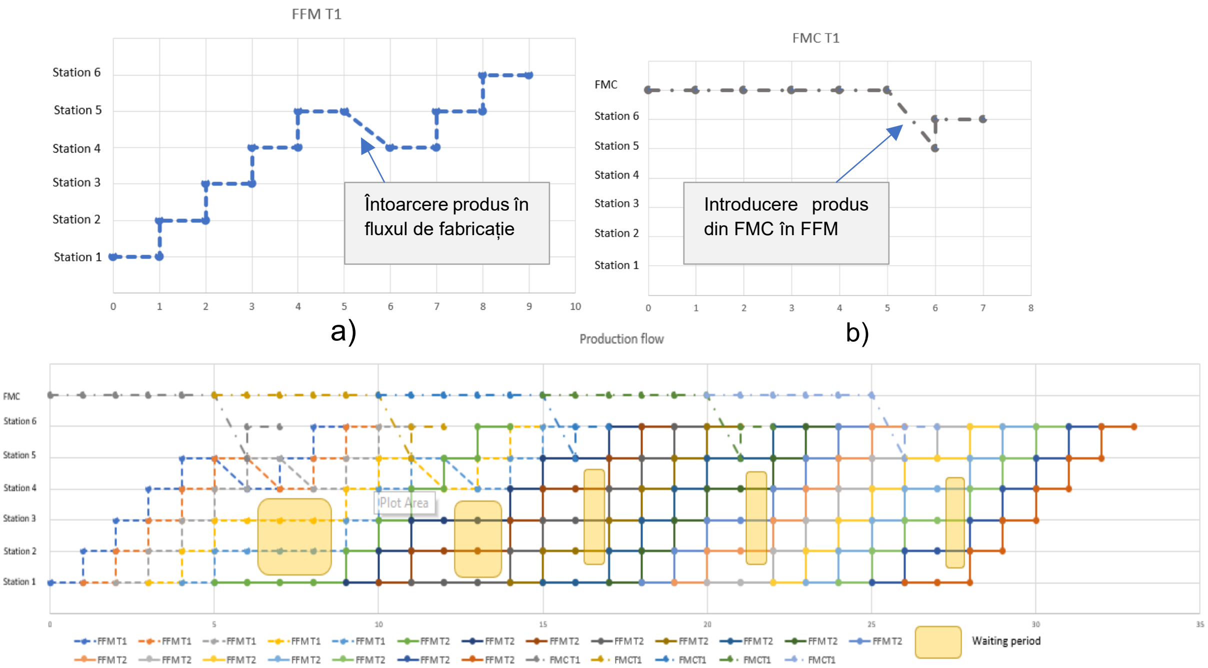
> In this section, the specific objectives of the **general objective OB.4** were achieved. Designing an optimal scheduling algorithm for hybrid manufacturing on a line with parallel production flows. The proposed algorithm is subject to the restrictions of minimizing the total manufacturing time and waiting times.
>
> **The algorithm for optimal planning**, designed for a hardware system for flexible manufacturing with parallel flows and a mixed product demand structure, is a significant contribution. This approach to manufacturing planning gives ISFM attributes specific to Industry 4.0 and 5.0, namely *sustainability* and *resilience*: the proposed algorithm ensures the balanced use of production system resources, respectively the balancing of the load on hardware resources, in accordance with the attribute of sustainability. Flexible manufacturing on ISFM can be planned through the optimal distribution of production volumes, or conversely, for small demand volumes, it can switch to simple planning, thanks to the resilience attribute.

Chapter 5

Implementation of the optimal scheduling of flexible manufacturing on parallel flows, in a specific approach to the concepts of Industry 4.0 and 5.0

In this chapter, a specific approach to Industry 5.0 is proposed, by introducing direct customer interaction - integrated system for flexible manufacturing, both in management structures and in manufacturing planning. From the intervention of the human operator in the process, through local HMIs, often optional, we have reached systems that place the human factor in the centre of decision and data collection, in the position of specialist, operator, or customer.

5.1. Implementation and testing of optimal scheduling of flexible manufacturing with two parallel flows. Case Study



a)

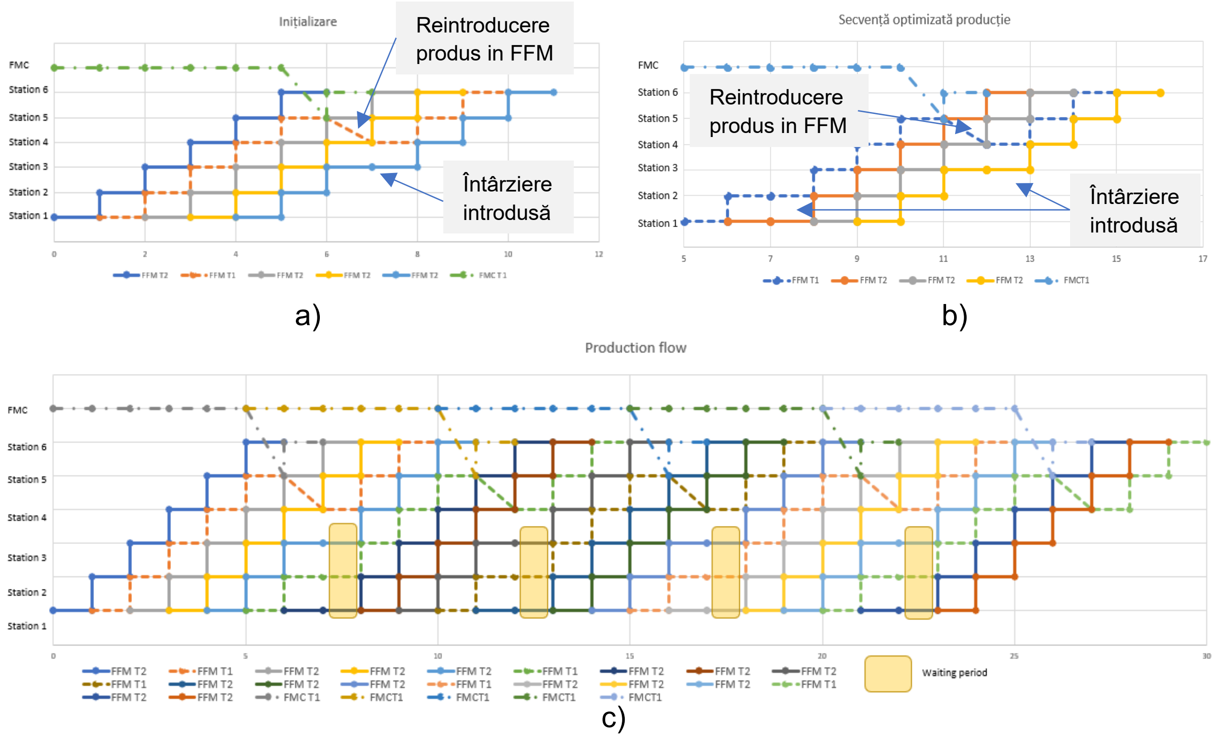
b)

d)

Figure 27. a) Planning the manufacture of a Type 1 product on FFM; b) Planning the manufacture of a Type 1 product on FMC; c) Planning the manufacture of a Type 2 product on FFM; d) Planning the production of a volume of 25 products, on the parallel FFM and FMC flows, without optimizing the waiting sequences

In the framework of the flexible manufacturing system, a production order consisting of 10 products of type 1 and 15 products of type 2 is assumed. If simple production planning is considered, an equal distribution of products with T_1, is applied to the processes, so that the distribution of products on the FFM and FMC flows becomes: 5 Type 1 products are directed to the FMC flow, 5 Type 1 products are directed to the FFM flow, and 15 Type 2 products are directed to the FFM flow.

From the comparative analysis of the results obtained for the two planning strategies, optimal and simple, Figure 56 and Figure 55, the following judgments can be made: the waiting time in the optimal approach is reduced by half, from $8 \cdot T_{prod\max}$ to $4 \cdot T_{prod\max}$ the use of production resources is improved in the optimal planning, by reducing the waiting time corresponding to the first three stations (Figure 56). In the case of simple planning, long waiting times are generated in the first four stations, for the manufacture of Type 1 products (Figure 55).



a)

b)

c)

Figure 28. a) The initialization sequence within optimal manufacturing planning; b) The optimal production sequence obtained as a result of planning; c) Optimal planning of the manufacturing of a volume of 25 products, on parallel flows FFM and FMC

5.2. Client-Server application for optimal planning of parallel manufacturing, in a specific approach to Industries 4.0 and 5.0

The implementation of the optimal planning algorithm required the modelling of the data collection process, processing and transmission of information, with specialized RP, RPS, RPT. The algorithm was interfaced with a Client-Server software application, which, through the Cloud server, will store the production requests, collected in real-time. The entire system is connected to the human factor, which thus becomes a central part in the dynamics of the process, a concept specific to Industry 5.0.

In the Industry 5.0 approach, the development of industrial systems cantered on the human factor, namely the direct involvement of the customer in the manufacturing process, ensures full transparency between the manufacturer and the social environment, in accordance with its needs and preferences. At the same time, the specific concepts of Industry 5.0., namely *sustainable manufacturing* and *environmental sustainability*, are reflected in the manufacture of customized products, with a minimally invasive impact on the environment. Through the software interface, production orders are taken at any time, without depending on the activity schedule of an operator, which leads to increased competitiveness but also to the extended addressability of potential customers

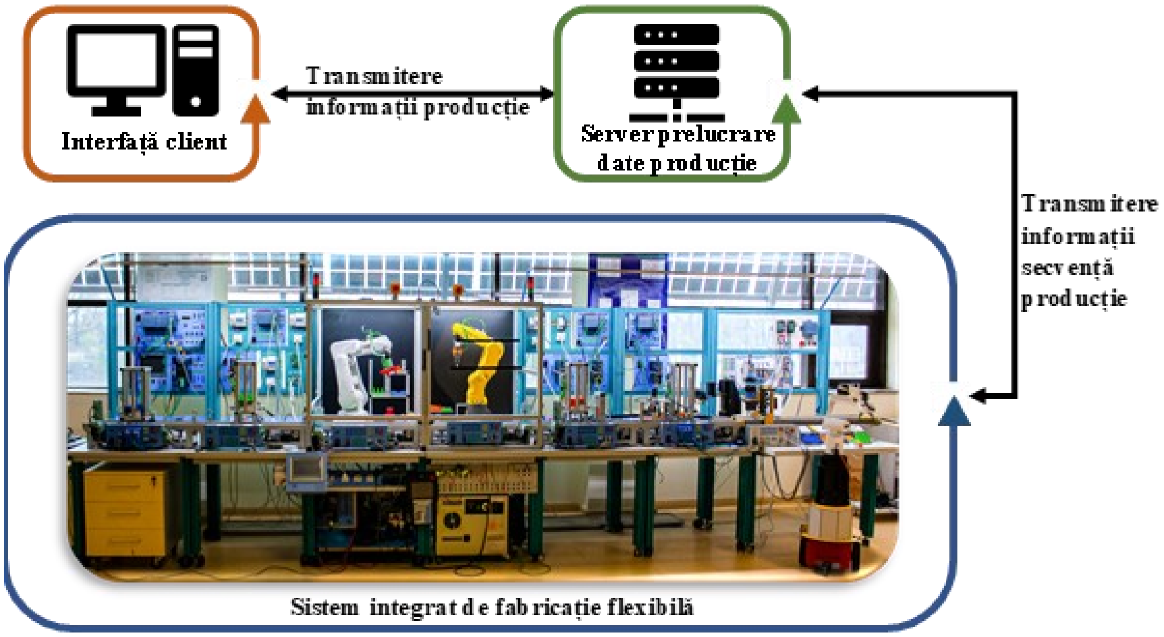


Figure 29. Customer – Manufacturing System data flow dynamics

5.3. Scientific results and contributions

In this section, the specific objectives of the **general objective OB.5**, regarding the implementation of an optimal planning algorithm for flexible manufacturing, with parallel flows, were achieved. The algorithm was customized on an integrated system for flexible manufacturing with two parallel flows. For the implementation of the algorithm, a software platform dedicated to the collection of production requests/orders, and the storage of this data on a *Cloud* server, was created. The algorithm was implemented and tested on production scenarios, and the results highlighted the efficiency and economic gain that the application of optimal planning brings. The convergence of optimal planning with real-time management of flexible manufacturing, allows the automatic adaptation of the system to different production demands, respecting the condition of high productivity, without additional consumption of hardware resources, which recommends it as an important scientific contribution.

A significant result of the research is the **integration of Industry 4.0 and 5.0 concepts** in the management of flexible manufacturing with parallel flows. Thus, the design and implementation of a **software_Client-Server platform** that ensures, through the *Cloud* server, the interfacing of the optimal planning algorithm, with the real-time takeover sequences of the production orders, as well as the monitoring of the production process. The Client-Server software platform reintegrates into the process the client / human factor who operates, in the client interface, customized production requests. Moreover, the customization of the product configuration that is launched in manufacturing, brings the human operator back to the control panel of the process, through the HMI Interface. The **software_Client-Server platform** hosted by the *Cloud* Server is a significant achievement in the sense of applying the concepts of Industries 4.0 and 5.0, relative to: the reintegration of the labour force in the industry, the application of distributed manufacturing, the hyper-customization of manufacturing. By integrating the concepts of Industries 4.0 and 5.0, the implementation of an ISFM appropriate to the concepts of sustainability of production resources, environmental sustainability, resilience, and reintegration of the human factor in industrial processes is achieved.

Chapter 6

Scientific conclusions and contributions

The development of complex systems for flexible manufacturing, assisted by robotic systems, equipment and advanced technologies specific to Industries 4.0 and 5.0, required the use of specialized modelling tools, RPT and RPS, as well as the implementation of structures for advanced management.

The entire approach of theoretical and experimental research, which used the logistic infrastructure of the *Research Laboratories of the Multidisciplinary Scientific and Technological Research Institute (ICSTM)* of Valahia University in Târgoviște, took place within the PN-III-P1-1.2-PCCDI research project -2017-0290, won through the competition Complex projects carried out in CDI consortia (PCCDI), PN 2345577, coordinated by the "Lower Danube" University from Galati [82]

This thesis has as its main contribution the design and implementation of techniques for adapting a manufacturing line in flow to an integrated system for flexible manufacturing, served by robotic systems, with the integration of Industry 4.0 and 5.0 concepts. The integrated system for flexible manufacturing was designed to respond to the integrative concept of total manufacturing, in the sense of implementing a complete cycle of operations, assembly, disassembly, recovery and reuse of components.

IFMS can work both as a system for the flow manufacturing of single-type products, and as a system for flexible manufacturing, having the ability to adapt manufacturing to different types of products - *manufacturing ranges*. Thus, the concept of diversified manufacturing was implemented from the point of view of product typologies, namely flexible manufacturing.

In conclusion, the application of Industry 4.0 and 5.0 concepts is embodied in original solutions and concepts for: ● designing the hardware structure to adapt flow manufacturing to flexible manufacturing on parallel flows; ● modelling and implementation of ISFM advanced management; ● implementation of robust management; ● optimal production planning; ●bringing back the human factor in the process, namely the operator / client and the HMI interface / Client-Server interface.

6.1. Scientific contributions

In this research paper, integrated scientific contributions are highlighted in concepts, hardware structures and control techniques for design, modelling, control implementation and optimal planning in order to adapt flow manufacturing to an integrated system for flexible manufacturing. These original scientific proposals were disseminated through works published in journals or at scientific events, organized by research directions in the field of Systems Engineering. The scientific contributions assumed in this endeavour are correlated with research concepts and axes, as follows:

- ✓ the design of an original process of flexible manufacturing in flow, in which the specific manufacturing of a manufacturing range and the manufacturing of products with diversified typologies, can be achieved by adapting a system dedicated to the manufacturing of a single type of product, with minimal hardware investments. [LS2], [LS5], [LS8];

- ✓ designing a manufacturing process in the cell, part of the integrated system for flexible two-flow manufacturing. [LS2], [LS5], [LS8];
- ✓ the development of an original technique for adapting flow manufacturing systems to integrated systems for flexible manufacturing. This approach offers solutions in the transformation of traditional production processes, to hybrid production systems, intended for flexible manufacturing, and/or manufacturing in parallel flows, specific to mass production [LS2], [LS4], [LS5], [LS7], [LS8];
- ✓ Implementation of techniques to adapt flow manufacturing systems to integrated flexible manufacturing systems, with the implementation of Industry 4.0 and 5.0 concepts. [LS3], [LS5], [LS6], [LS7], [LS8];
- ✓ using advanced modelling techniques with RPS, and simulating the assembly process on an integrated system for flexible manufacturing. [LS2], [LS4], [LS7], [LS8];
- ✓ the use of RPS for modelling and simulating the assembly process in IFMS workstations, highlighting the synchronization of their interconnection. [LS2], [LS4], [LS7], [LS8];
- ✓ development and implementation of an algorithm for control of the transport of products on the conveyor, for precise positioning, at the work point in the station. [LS1], [LS9];
- ✓ development and implementation of an algorithm for optimal planning of production tasks, within IFMS. [LS2];
- ✓ creation of an interactive Client-Server application, for the acquisition and transmission of production data. The Client-Server application, through the Cloud server, allows the user to make a customized production request [LS4].

6.2. Future research directions

Considering the results obtained in this PhD thesis, possible future research directions have been identified:

- development of an advanced application for the total management of the manufacturing system;
- the development and integration of an innovative Digital twin concept, within the control loop of the manufacturing system's conveyors, for fast positioning, with a high degree of precision, and with disturbance compensation;
- the incorporation of autonomous mobile robots into the flexible manufacturing system, through specific embedded systems management technologies, to improve product handling, transport and assembly operations;
- implementation of Big Data concepts, through the efficient collection and analysis of production data;
- the introduction of intelligent sensors in the flexible manufacturing process for the local detection of production defects and their integration into a continuous product quality monitoring system;

- implementation of augmented reality concepts in order to design the sequences of operations for making products and troubleshooting manufacturing systems.

6.3. Dissemination of results

The dissemination of the results was done by publishing the research results in 9 (nine) publications - journals and conference proceedings, on 7 (seven) of these having the quality of the main author, as follows:

- 5 papers presented at IEEE Xplore international conferences indexed ISI proceedings Web of Science (WoS);
- 4 papers published in ISI Web of Science indexed journals.

6.3.1. Scientific papers published in journals

[LS1]. **Duca, O**.; Minca, E.; Filipescu, A.; Cernega, D.; Solea, R.; Bidica, C. *Event-Based PID Control of a Flexible Manufacturing Process*. Inventions 2022, 7, 86, WOS:000902580500001, ISSN: 2411-5134, https://doi.org/10.3390/inventions7040086

[LS2]. **Duca, O.;** BIDICĂ, C.; Minca, E.; Gurgu, V.; Marius, P.; Dragomir, F. *Optimization of Production Planning for a Flexible Assembly Technology on a Mechatronics Line*. Studies in Informatics and Control, 2021, 30, 53–66, WOS:000636266000005, ISSN: 1220-1766, https://doi.org/10.24846/v30i1y202105

[LS3]. Paun, M.; Gurgu, V.; **Duca, O**.; MINCA, E. *Image Processing Method Based Quality Test On A Smart Flexible Assembly Mechatronic System With Component Recovery*. Journal of Science and Arts, 2020, 20, 1037–1048, WOS:000604620700024, ISSN: 1844-9581, https://doi.org/10.46939/J.Sci.Arts-20.4-c05

[LS4]. **Duca, O.** ; Minca, E.; Paun, M. A.; Gurgu, I.V.; Dragomir, O.E.; Bidica, C. *Petri net modeling of a production system with parallel manufacturing processes.* Journal of Science and Arts. 2023, 23(1), 305-318, ISSN: 1844-9581, https://doi.org/10.46939/J.Sci.Arts-23.1-c05

6.3.2. Scientific papers published in proceedings at international conferences

[LS5]. **Duca, O**.; Gurgu, V.; Minca, E.; Filipescu, A.; Dragomir, F.; Dragomir, O. *Optimal Control of the Complete Assembly/Disassembly Cycle for a Mechatronics Line Prototype.* In Proceedings of the 2019 23rd International Conference on System Theory, Control and Computing (ICSTCC); 2019; 620–625, WOS:000590181100105 , ISSN: 2372-1618, https://doi.org/10.1109/ICSTCC.2019.8885824

[LS6]. Paun, M.; Minca, E.; Filipescu, A.; Filipescu, A.; **Duca, O**. *Improved Image Processing Algorithm for Quality Test on a Flexible Manufacturing Mechatronic Line*. In Proceedings of the 2020 24th International Conference on System Theory, Control and Computing (ICSTCC); 2020; 819–824, WOS:000646582900135, ISSN: 2372-1618, https://doi.org/10.1109/ICSTCC50638.2020.9259655

[LS7]. **Duca, O**.; Minca, E.; Filipescu, A.; Bidica, C.; Paun, M. *Optimal Control of Automated Resupply on a Flexible Manufacturing Mechatronics Line.* In Proceedings of the 2020 24th

International Conference on System Theory, Control and Computing (ICSTCC); 2020; 921–926, WOS:000646582900152, ISSN: 2372-1618, https://doi.org/10.1109/ICSTCC50638.2020.9259660

[LS8]. **Duca, O**.; Minca, E.; Paun, M.; Gurgu, V.; Dragomir, F.; Bidica, C. *Modeling and Control of Assembly/Disassembly Manufacturing Line Redesigned from Flux to Flexible Manufacturing*. In Proceedings of the 2021 25th International Conference on System Theory, Control and Computing (ICSTCC); 2021; 535–540, WOS:000859487900088, ISSN: 2372-1618, https://doi.org/10.1109/ICSTCC52150.2021.9607071

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