The National University of Science and Technology

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Doctoral School

Faculty of Industrial Engineering and Robotics

DOCTORAL THESIS

RESEARCH ON THE STRATEGY OF CYBERNETIC INTEGRATED INDUSTRIAL PROCESSES

SUMMARY

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Contents

List of abbreviations

AAS – Asset Administration Shell

AIAL – Lean Instrument Management Application

AIAO – Object Management Application

AIAOC – Complex Object Management Application

BDRT – Real-time Database

CPS / CPMS – Cyber-Physical System / Cyber-Physical Manufacturing System

CPSL – Lean Cyber-Physical System

DMC – Dynamic Matrix Control

ERP – Enterprise Resources Planning

HCF – Cyber Physical Holon

HMI – Human Machine Interface

IoT / IioT – Internet of Things / Industrial Internet of Things

IRDI – International Registration Data Identifier

ISO – International Organization for Standardization

MaaS – Manufacturing as a Service

MAIAL – Meta-application for the management of the adaptive integrated manufacturing system

MES – Manufacturing Execution System

MPC – Model Predictive Control

PaaS – Platform as a Service

PLC – Programmable Logic Controller

RAMI 4.0 – Reference Architecture Model Industry 4.0

RISA – Network Asynchronous Cybernetic Subsystem of Manufacturing Processes

RISS – Cybernetic Synchronous Subsystem of Manufacturing Processes Information Network

RTLS – Real-Time Location System

SaaS – Software as a Service

SBDF – Database Subsystem of Manufactured Products

SBDI – Integrated Database System

SBDP – Database Subsystem of Manufacturing Processes

SBDR – Database Subsystem of Manufacturing Resources

URI – Uniform Resource Identifier

XaaS – Everything as a Service

Introduction

Industrial production systems are changes subject of the economic environment due to the increasingly high demands and requirements related to prices, product quality and specific consumer needs. These pressures are transferred to the manufacturing subsystems in the form of optimization requirements, increasing flexibility and reducing variability, with the aim of increasing the agility of system and ensuring increased economic efficiency on the market.

The decision-making level interventions and the support given to transformation-innovation projects as a result of new manufacturing philosophies adoption, have led to significant developments in automated industrial manufacturing systems (flexible, programmable, robotic or collaborative). In recent years, the established technologies development and new technologies emergence (manufacturing, communications and information processing) gain attention and, through their adoption rates, have been perceived as solutions for achieving agile, flexible or lean manufacturing. Main system characteristic is the external and internal factors sensitivity, and is due to the integration into ecosystem in which the parties interact and act according to a common set of objectives.

The computer-integrated manufacturing process is closely related to the latest advanced concepts, such as smart manufacturing, distributed manufacturing or mass customization.

This new production system paradigm is based on the accessibility of high computing power, the communication systems performance, the cloud storage growth and the increase in the capacity of real-time modeling and rendering, also to the cloud services availability, which have become much more reliable, scalable, and become an indispensable resource for computer-integrated manufacturing systems in order to deliver high performance for a low cost. Through cybernetic integration, the production system, the manufacturing system and the manufacturing processes has led toa new concept emergence, called Industry 4.0 or the fourth industrial revolution. This concept describes an autonomous, efficient production system, embodied in the form of a smart factory, in which people, resources and machines communicate and collaborate to manufacture products as a result of intelligent manufacturing processes, integrated into the value chain.

This thesis contributions offers a complete IT integration solution for automated industrial manufacturing process. The solution is developed in the form of a strategy, who addresses the technological transformation process, which aims to cybernetic integration of industrial processes and realising the cyber-physical manufacturing system.

1. The current stage of the manufacturing system

1.1.History of manufacturing systems

As concept, manufacturing system was introduced in the 19th century with the meaning of factory system (33), describing the effort to optimize and simplify production as a system (34). The manufacturing system is described as an assembly of buildings, equipment, machines, devices and workers, through which raw materials are transformed into goods (2). Mass productionwas the first paradigm that influenced the manufacturing systems evolution, describing the manufacturing of large batches product, at the required quality and at an efficient cost.

With logic programmer controller, a new industrial concept emerge under the name of flexible manufacturing system. The evolution of production technology and information systems has led to a new concept, of intelligent manufacturing, through which the use of existing knowledge leads to a new knowledge (6).

1.2. Industrial Automation and Smart Manufacturing System

Automation refers to the control of industrial processes and machines through command and control devices. The automated manufacturing system architecture is presented in a hierarchical form, describing the detection level, the manufacturing cell level, the manufacturing level, the automation level, and the enterprise level (37).

To access a level of intelligence, the manufacturing system are equipped with extensions who interact or communicate with the environment, people or other subsystems, providing information about the system state, and supervised processes. It also allows for increasing the level of automation and machine intelligence, and useing robotics in industrial processes (32).

Smart Manufacturing is an integrative concept, which approaches the manufacturing system as an innovation center by integrating industrial automation with advanced manufacturing technologies. The technologies that underpin are intelligent machines and industrial robots, the Industrial Internet of Things, Cloud services, Big Data (30) (see Fig.1.1).

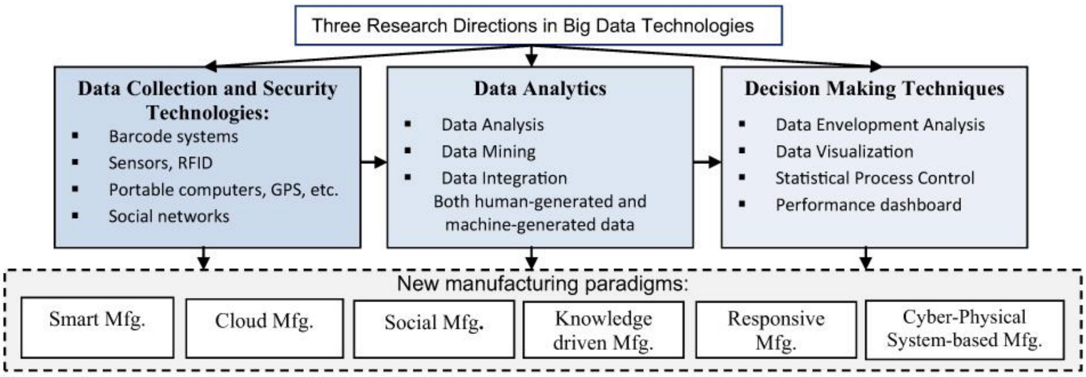


Fig. 1.1: Smart manufacturing technologies and new manufacturing concepts (41)

According to this concept, technologies are involved in the intelligent control and resources management, which are virtualized and service oriented (31). This opportunity was seized by the German Association of Electrical and Electronic Equipment Manufacturers, which defined a new concept, Industry 4.0, and for which it developed the RAMI 4.0 reference model (42).

The Industry 4.0 concept has been defined as the evolution of smart manufacturing, a new stage of industrialization and is an integrated, intelligent computerized production system, in which products and services are connected, allowing for a fully automated, digitalized and self-configurable production, whose elements are autonomous (20), and cyber-physical system supervized smart factory processes, it formulates decentralized decisions, communicates and cooperates with physical system (21).

The objectives of production system are horizontal integration of production systems in which value is created, vertically integration of manufacturing systems and the subsystems associated with chain value, as well as to integrate the product life cycle (51). The computer-integrated production system must define each of its components at digital level, in the form of a digital application (52).

1.3. Manufacturing holonic system

The holonic manufacturing system is made up of the cyber-physical structures as result of the virtualization of the entities of the physical manufacturing system to access and distribute intelligence, as well as to integrate learning capabilities to achieve the adaptive and evolved manufacturing system (55). The manufacturing holon is an autonomous and cooperative structure designed to transformation, transport and storage of physical or informational objects. A holon can be formed from other holons, forming a holonic system (holarchy) that cooperates to achieve manufacturing goals and can be dynamically created or dissolved, depending on manufacturing process needs (55). The agile holonic manufacturing system is reconfigurable, dynamic, scalable (can integrate new manufacturing holons) and intensively information processing (56).

1.4. Advanced manufacturing technologies

Advanced technologies transforming the existing system into an integrated IT system and allows the system to be updated through incorporate of new technologies at basic level or complementary operations (19). They are classified and analyzed according to implementation type, the operational area or organizational level served the integration method or the information capabilities (26) (27). Advanced technologies used in the transformation of manufacturing systems through IT integration are additive manufacturing, big data, advanced materials technology, advanced robotics, artificial intelligence, biotechnology and biofabrication, personalized IT networks (Blockchain), cybersecurity, DDSI technologies (Digital Design/Simulation/Integration), high-performance computing systems, intelligent interfaces, Internet of Things (IoT) (19).

1.5. Advanced manufacturing technologies adoption

Technology is the new knowledge application to practical issues through the science application, which aims to gain knowledge through observation and search for truth (94). Advanced manufacturing technologies are divided into computing equipment (hardware – networks, computers, interfaces, instruments, sensors, etc.), software applications (CAD, CAM, Computer Aided Process Planning, Data Base Management System, Material Requirements Planning, Manufacturing Resource Planning, Supervisory Control & Acquisition Data, etc.), and manufacturing equipment (Programmable Logic Control Machines or Processes, Materials Working Lasses, Robots with Sensing Capabilities, Robots w/o Sensing Capabilities, Rapid Prototyping Systems, High Speed Machining, Flexible Manufacturing Cells, Automatic Assembly, Automated Warehousing/Order Picking, etc.) (60). These technologies can be individually applied (CAD, CAPP), as technological solutions (e.g. Automated Guided Vehicles System, AVGS) or as integrated technological systems (flexible manufacturing system, Computer Integrated Manufacturing) (9) (95).

The technologies that enable integrated cybernetic manufacturing systems are divided into two categories: basic technologies (which enable connectivity and the capabilities of supporting technologies) and supporting technologies (which ensure physical subsystems transforming into intelligent subsystems) (16).

To become intelligent, the system must intervene in the information flow between the equipement who interpret the environment and the reacting elements that detect changes in the environment, and be able to introduce the necessary adjustments to the system in order to have cognitive properties (97). This connection allows the manufacturing system to become an intelligent and self-adaptive (98).

1.6. Cyber integrated manufacturing systems implementation

Cyber-physical systems can be interconnected and can use information provided from production system. In order to communicate, the system digitized elements must be defined. These elements are included in the cyber-physical system through an computer application (AIAO) (99), witch is a standardized digital representation of a physical or logical object of a production system. It represent the object, different digital models of the object (submodels) and the technical functionality (100).

The implementation of applications is carried out at the operating concept level that describes the behavior of operating modules (101). Into the management application these definitions include characteristics, functionalities and references, internally associated with the asset (development software applications, embedded extensions, etc.) and externally, for use and maintenance (production capacity, technical data sheets, marketing information, the associated service acquisition process, etc.) (23). Through digitization, the components become available, interoperable and can be integrated into autonomous systems or can become subjects of artificial intelligence (103).

The information included is standardized, interpretable and refers to all aspects related to the functionality of the represented physical asset. These descriptions are individualized in the form of structured submodels, code sequences, through which the representation is achieved (105).

When the manufacturing resources AIAO's are defined, the digital copy of the manufacturing system and the CPS system is created by mapping submodels involved in the production process. After mapping, the meta-AIAO is compiled into an executable application that will be applied to run the manufacturing process, according to the scenario(106).

1.7. Algorithms

Efficient solution for automated manufacturing systems refers to an algorithm (a complex task) applied to the system mathematical model, which describes the problem to be solved (production planning, scheduling, or sequencing), and can be conceptual, analytical, artificial intelligence, or simulation, addressing the type of problem to be solved, manufacturing objectives, batch size, manufacturing or resource constraints (128).

Algorithms are classified into optimization algorithms – they provide the best possible solution, heuristics – they provide an optimal, practical and sufficient solution, metaheuristics – they provide a higher-level solution, in an iterative process, and mathematical algorithms – a combination of heuristic algorithms and optimization methods (129)

The Model Predictive Control is widely used in manufacturing automation control engineering, it is a multivariable model that uses performance parameters to control the system, is able to manage system constraints, performs optimization and manage complex processes in real time (134). The result is a controller that uses a mathematical model of process representation to predict the outcome execution (prediction horizon) and apply a control sequence to minimize the objective function and reduce variability (135). It is a feedback control technique for optimizing processes, operational planning and resources, in real time (136). The structure of Model Predictive Control is prediction model (how to determine what might happen), the objective function (the measurement tool) and the control function (the control implementation) (135).

The objectiveis to achieve the best prediction of process behavior for the next instance: $\hat{y}(t+k / t)$.

Through state space modeling, a physical manufacturing system mathematical representation is realised through a set of input and output variables, and a set of state variables. The representation uses two state equations (134):

$$x_m(k+1) = A_m x_m(k) + B_m u(k) + B_d \omega(k) \qquad (1)$$

$$y(k) = C_m x_m(k)$$

The Model Predictive Control algorithm uses a process model to calculate a manipulated variable in order to optimize and predict the evolution of a performance objective (134). It use the system variables values, calculates internal state variables, according to the model constraints, evaluates the objective function, and the controller communicates the best set of inputs to introduce the behavior adjustments according to the predictions (134).

The state variables can be defined as a sum of the effects of the input and output variables in the form (134):

$$y(k) = \sum_{i=1}^{n} aiy(k-i) + \sum_{i=1}^{m} biu(k-i) \qquad (2)$$

A mathematical model of the system is obtained, where the necessary described coefficients are determined, and a transfer function is applied to obtain the discrete state space model (137).

In this way, the continuous system operators are transformed into multiplication operators that describe the discrete system (134).

The next step is to design a Dynamic Matrix Control (DMC) that allows the system's behavior predictions. Also, calculations can be performed to determine the system variables evolution, and update the internal state (138). For each step (k), the DMC calculates the next instance Y(k+1/k) for the model's control horizon, within the optimal prediction horizon (138). Also, the reference values are calculated according to the process stationary model with the aim of determining a control sequence that will lead the system to the reference values, in an optimized manner. The optimization is done by determining the control variables and objective function optimal values (137):

$$\min_{usp,ysp} Js = c^T u_{sp} + d^T y_{sp} + e_y^T Q_{sp} e_y + e_u^T R_{sp} e_u + C^T T_{sp} C \qquad (8)$$

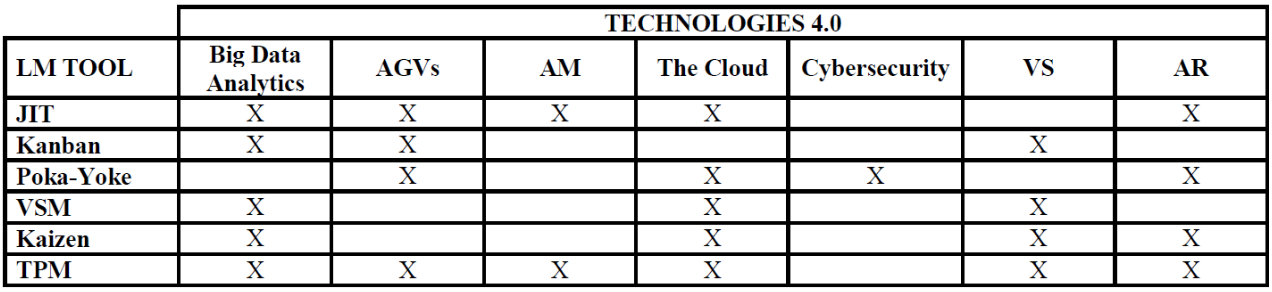
1.8. Lean 4.0 Manufacturing Systems

The Lean concept is seen as a solution for reducing the complexity of automated production systems (140). One of the latest developments refers to integrate the Industry 4.0 concept at the level of an adaptive production system and suggests to generate value through the automation of repetitive processes (141). There are also points of view that consider Industry 4.0 to be the next evolutionary stage of the adaptive production system (142) by adoption of Industry 4.0 technologies, whitch allows the rapid organization and reorganization of manufacturing cells according to the flow, volumes or mix of manufactured products (144).

In the Industry 4.0 concept, a set of fundamental technologies have been identified through which waste are identified and eliminated (145).

Related to computer integrated manufacturing, adaptive manufacturing is considered a slow system, with limited applicability in terms of process flexibility, small batch production or rapid system response, but the advantages offered mobilize efforts to identify solutions for integrating these values into autonomous and flexible manufacturing systems (28).

The current stage emphasizes the possibility of using advanced technologies to define adaptive manufacturing tools and practices in the context of computer integrated manufacturing For each Lean 4.0 tool, several technologies are identified that can provide support for integration (see Fig. 1.2) (28).



	TECHNOLOGIES 4.0						
LM TOOL	**Big Data Analytics**	**AGVs**	**AM**	**The Cloud**	**Cybersecurity**	**VS**	**AR**
JIT	X	X	X	X			X
Kanban	X	X				X	
Poka-Yoke		X		X	X		X
VSM	X			X		X	
Kaizen	X			X		X	X
TPM	X	X	X	X		X	X

Fig. 1.2 Fabricației adaptabile în sistemul de fabricație integrat informatic (28)

The computer integrated manufacturing concept is based on aquisition and analysis.

The Lean 4.0 system is an integrative model between the concept of computer integrated manufacturing and the principles of Lean Manufacturing, resulting in an intelligent, flexible and reconfigurable system that meets the Industry 4.0 manufacturing systems (154).

1.9. Current stage conclusions

The evolution of information technology led to the emergence of the concept of smart manufacturing. Through new technologies adoption, the Smart Manufacturing concept leads to new concepts, such as Industry 4.0, virtual manufacturing, and Cloud Manufacturing.

The Industry 4.0 concept has been defined as the next stage in the evolution of smart manufacturing, being considered a new stage of industrialization. Industry 4.0 describes an integrated, intelligent computerized production system, in which products and associated services are connected, and the system environment allows for a fully automated, digitalized and self-configurable production, in which the value chain is presented in the form of a decentralized network whose elements are autonomous.

Academic research highlights the attention paid to achieving flexibility, scalability and adaptability of the entire system by identifying the physical and cyber resources, also the capabilities necessary to achieve manufacturing objectives.

In the Industry 4.0 concept, a set of fundamental technologies have been identified through which waste are identified and managed, and the technologies that underlie the Industry 4.0 system. Transforming strategies must take into account the type of technologies adopted, updating manufacturing processes or business model. The objective of these strategies is to materialize the smart product, smart work, smart manufacturing and smart supply chain.

To achieve the integrated information production system, the strategy establishes the mix of applicable technologies to the existing production system. This mix consists of basic technologies (which enable connectivity and support of supporting technologies) and supporting technologies (which provide the system with the capabilities necessary to transform physical systems into intelligent subsystems).

The implementation of the technological strategy must lead the production system at a cognitive level by redefining the system objectives and modifying behavior. This will provide self-control, self-optimization and self-adaptability capabilities.

The new architecture of the physical manufacturing subsystem allows integration with the cybernetic system, obtaining holonic systems, through which configurations of manufacturing cells or the entire system are assembled or disassembled.

The algorithm implementation allows components digitalization and integrating computerized manufacturing system. The choice of the type of algorithm is based on the advanced manufacturing technologies incorporates. The predictive control model is multivariable, used to achieve performance of the control system, manages constraints, and performs processes optimizations in real time. The MPC model is based on targeted system mathematical model, which allows complex performed computation, which result in a control sequence applicable to the managed system and the prediction of the behavior.

2. Research objectives and methodology

2.1. Research objectives

O1. Defining a manufacturing system cybernetic integration strategy.

O2. Identify a data management system, according to the cyber physic manufacturing concept.

O3. Desingning a management architecture of cyber manufacturing system.

O4. Develop an algorithm for cyber integration of an asset into cyber physical system.

O5. Identifying a strategy to implement the cyber integrated lean manufacturing system.

2.2. Methodology

The research methodology needed to achieve the objectives:

E1. For identifying a strategy for cybernetic integration consist of studying the research current state and evaluating aplicable scientific achievements.

E2. In order to define digital structures for data management, is need to study latest achievements in database management and information, from manufacturing cyber integrated systems view.

E3. Evaluate the aplicable researches directions, regarding the management of automated manufacturing systems, integration technologies and architectural models.

E4. For identify and design an algorithm, is needed to asses the current state of research suitable for application at manufacturing systems level.

E5. To identify the strategy for defining the adaptive manufacturing system, it is necessary to study scientific approaches regarding the advanced technologies used to cyber-integration of adaptive manufacturing systems.

3. Contributions regarding the strategy of cybernetic integrated industrial processes

3.1. Manufacturing cyber physical system integration

Integration is based on the capabilities provided by information and communication technology and involves a process of transformation, in which existing subsystems increase in complexity to be integrated into the production ecosystem.

The cyber-physical manufacturing system has cognitive properties, who interacts, interprets and reacts with its environment. To reach the cognitive level, the system acquires, stores and process data, as well as using them to adjust processes or behavior. The integration technology is the cyber-physical system (CPS), who retains the characteristics of automation, and added cognitive capabilities offered through cyber integration.

The CPS architecture consists of:

1. The physical manufacturing subsystem – made up of machines, devices, sensors, actuators, etc.
2. Cybernetic subsystem – digital copy of the physical production system.
3. IT&C subsystem – hardware, connectivity and data management applications.

From this perspective, integration must be carried out for each subsystem of CPS.

The self-configurable automated system is achieved by updating manufacturing assets with manufacturing equipment and extensions (component systems) that allow the reconfiguration of manufacturing lines or manufacturing cells according to the requirements for the execution of product batches. This objective is complemented at the cybernetic system level with requirements for automating the corresponding processes and implementing algorithms for supervising and correcting the manufacturing flow. By meeting these objectives, the manufacturing system is prepared for connection and integration with the cybernetic system, the architecture providing solutions for reconfiguration and self-organization (See Fig. 3.1).

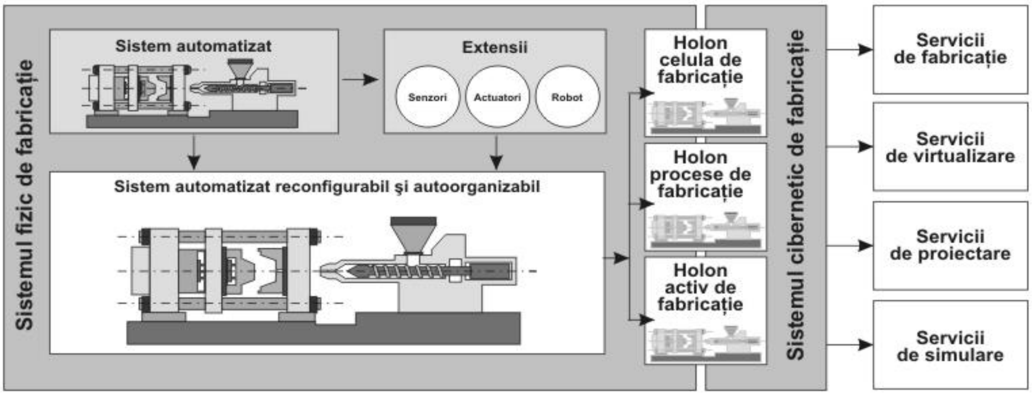


Fig. 3.1 Automated manufacturing system update

3.1.1. The cybernetic manufacturing subsystem

On the cyber subsystem level, the digital copy of the manufacturing system is defined, the digital models of automation, manufacturing processes, products and services are designed, as well as the structure of the information system. For manufacturing systems, the main capabilities are found in the areas of data collection, storage and processing, communications, process control and management capabilities. Depending on the the data collected porpose, the cyber subsystem is divided into synchronous and asynchronous data of manufacturing processes (See Fig. 3.2).

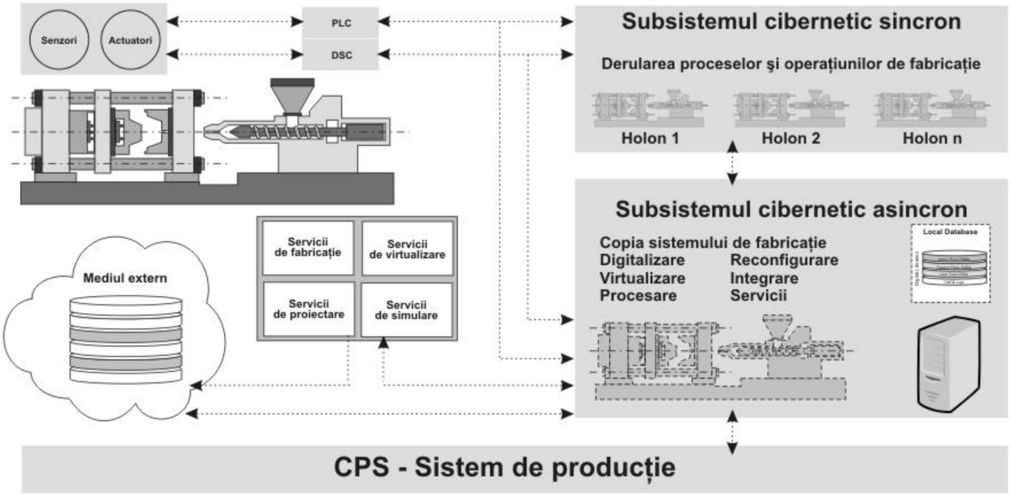


Fig. 3.2 Sistemul cibernetic – subsistemele sincron și asincron

3.1.2. Defining the manufacturing system digital copy

The application for managing an object (AIAO) is the basic element through which a digital copy of the manufacturing system is created. This application is a digital, standardized representation of a manufacturing asset, physical or logical. By defining all manufacturing assets as AIAO, the representation of the entire manufacturing system through its components is achieved. The content is structured in modules, which organize this information into:

- technical data - about the represented asset
- operational - used to integrate asset

Constructively, the AIAO module constitutes a reference to an attribute, function or component of the represented object.

The content is structured according to addressability of the embedded information (synchronous or asynchronous system of manufacturing processes), witch allows to define services for:

- physical or digital manufacturing assets
- manufacturing processes
- manufacturing resources (digital or physical)
- manufacturing capabilities

In the form of complex AIAO's (AIAOC), the system is capable to applying different scenarios, to running complex processes, various simulations.

3.1.3. The synchronous cybernetic subsystem of manufacturing process

Through IT integration, the structure engaged in manufacturing processes creates a coherent system that manages the assets properties, the operating succession, the components relationships, and the resources. This structure, along with the manufacturing AIAOC, defines a cyber-physical holon (HCF) of the integrated manufacturing system architecture (see Fig. 3.3).

The transformation is achieved by differentiating the elements actively involved in manufacturing processes from the passive ones, which do not change when moving from different manufacturing scenario to ensure continuity of the processes (157).

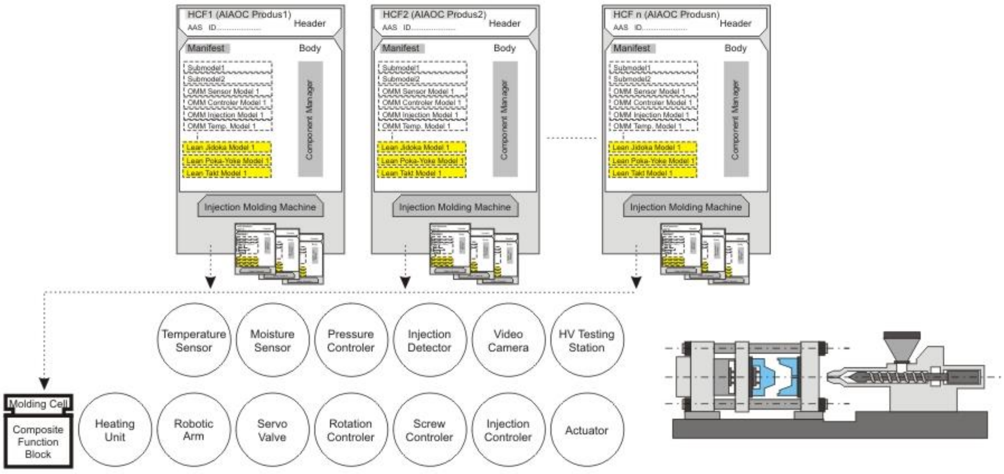


Fig. 3.3 Synchronous cybernetic subsystem holons

3.1.4. The synchronous cybernetic subsystem of manufacturing process

Asynchronous processes manage a different structure involved into manufacturing processes but impact their upstream execution – by integrating superior cybernetic skills that increase execution performance, during process execution – by formulating and adopting superior decisions for system adaptation to the manufacturing environment, and downstream – by increasing adaptability, predictability, and integration into the value chain or manufactured products life cycle.

While synchronous cybernetic system is limited by the physical assets attributes and properties, and the physical manufacturing system capabilities, the asynchronous cybernetic system has a versatile architecture, which allows:

- the system organization/reorganization (vertical integration)

- manufacturing system scalability
- horizontal CPS integration
- connection the manufacturing system with the production system

The main objective of the asynchronous cybernetic system is the design, analysis and validation of complex AIAOC structures that define cyber-physical holons. After modeling, simulations are run to assess integrity, interoperability and cybersecurity.

The asynchronous cyber system scalability occurs on two dimensions. This can be quantitative, through the cyber integration of new physical manufacturing assets, and qualitative. Qualitative scalability is made by increasing the capabilities of the system through technological innovation, incorporating new algorithms or adopting cognitive processes.

3.1.5. The information subsystem implementation

The information subsystem main goal is to achieve internal synchronization of manufacturing system. From this perspective, the information subsystem is formed by several networks:

a. The synchronous manufacturing processes IT&C network
b. The asynchronous manufacturing processes IT&C network
c. The external network of production system

3.1.6. The synchronous manufacturing processes IT&C network

This network ensures:

- The cyber-physical holon implementation defined by AIAOC
- Communication between devices and equipment
- ensuring interaction of manufacturing system with environment
- collection and transmission of data
- manufacturing systems command and control

The goal synchronous manufacturing process system network (RISS) is to synchronizing the production cell with the HCF, as well as connecting the synchronous system to the asynchronous cybernetic system.

The management of RISS is done by the server level, which takes over the production scenario, defined by AIAOC at the CPS level, and builds the manufacturing HCF. The physical connection is achieved through the communications network, consisting of cabling, routers, switches, WiFi devices.

3.1.7. The asynchronous manufacturing processes IT&C network

The asynchronous cyber subsystem collect the advanced technologies capabilities. The asynchronous cyber subsystem network architecture (RISA) is designed to integrate manufacturing system different areas to perform specific processes, through hardware and software support.

Connecting active areas through RISA allows the CPS interpretation as a mix of services (in relation to the external environment) or processes (in the internal configuration of the production system), which improve economic efficiency (external) and increase flexibility (internal) by increasing internal coordination and synchronization.

3.2. Database Cyber System

Through cybernetic integration, the capabilities necessary to achieve a flexible, programmable, reconfigurable, self-adaptive, evolutionary, available and intelligent manufacturing system are added. Information values data in order to integrate essential elements of the physical manufacturing system:

- Machines and equipment
- Human resources
- Raw materials

This results in cyber integration of main sources of value added:

- Manufacturing assets
- Labor
- Manufacturing product processes

From this perspective, the cybernetic integration of manufacturing system requires an integrated data management and analysis structure.

3.2.1. Manufacturing Assets Database Subsystem

The goal of manufacturing resource database subsystem (SBDR) are virtualization of the physical manufacturing system (machines, people and raw materials), to define digital models of automation and to describe the capabilities needet to integrate the manufacturing system. The MBDS model is relational, where the manufacturing resources are logically structured. By design, the MBDS structure allow CPS to select the capabilities, characteristics and functionalities of physical entities in the form of AIAO, and to provide the necessary support for archiving AIAOC.

3.2.2. Manufacturing Process Database Subsystem

The Manufacturing Process Database Subsystem (SBDP) ensure a constant and continuous data flow for CPS, between the physical subsystem and the digital copy of the manufacturing system that carries out the operations. The objective is to facilitate the interpretation and adaptation to environmental variations and to ensure manufacturing processes continuity .

The SBDP architecture ensure the necessary data for AIAOC integration and defining CPS holon. The CPS management system evaluates the performance of processes according to a predefined set of KPIs. For this purpose, a database is established at the SBDP level, fed by querying historical data in order to process relevant data. The results of the analyses constitute inputs in the operational database for evolution recording and for use in asynchronous evaluating processes.

3.2.3. Manufacturing Product Processes Database Subsystem

In the process of transforming raw materials into finished products, there is a moment when the product receives a unique identity (barcode, QR code or RFID, for example). From that moment on, information about its properties, state, use or consumption becomes available and is included in the product life cycle.

The manufactured products database subsystem (SBDF) connect the manufactured product with the transformation environment, introducing it into its own life cycle and integrating it into the value chain of production system. The database provides CPS with information necessary to identify the manufacturing solution. The product data are transacted as outputs to a large database, which can be located locally or to a large cloud database, via the Industrial Internet of Things (IIOT).

3.2.4. Database Cyber System Management

The integrated computer database system architecture (SBDI) requires a management solution for each subsystem. According to it, the management system is structured as a modular platform, according to the three subsystems (SBDR, SBDP și SBDF).

Due to importance, we have defined the architecture of the integrated computer database system that describes the distribution of information, designed for the physical manufacturing subsystem, the cyber subsystem and the information subsystem (see Fig.3.4).

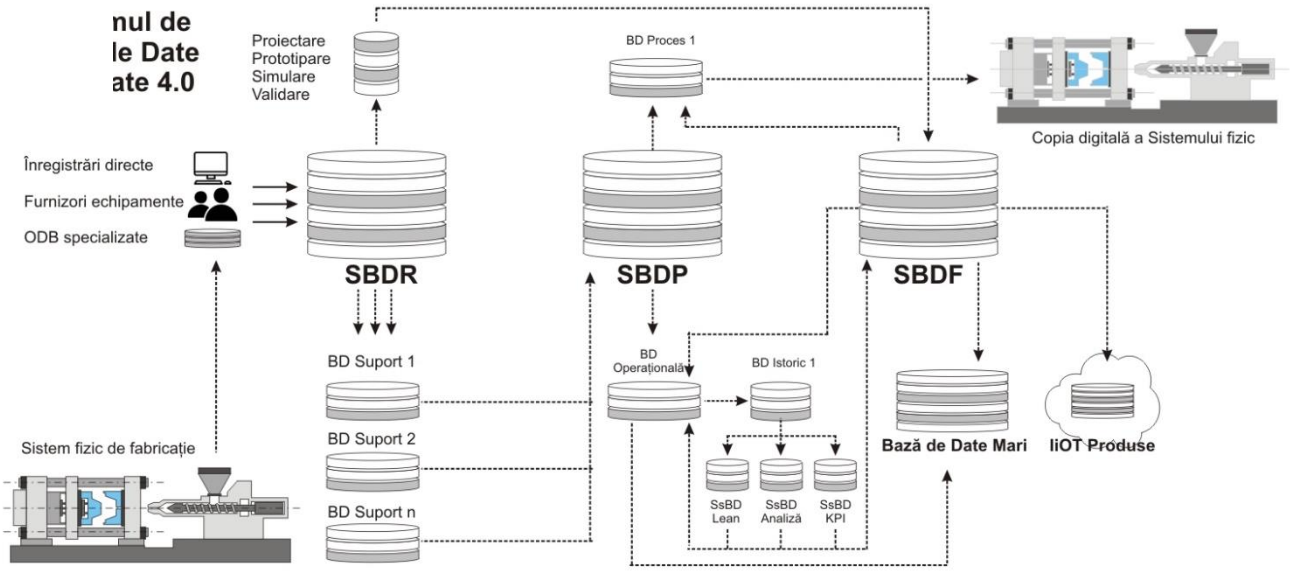


Fig. 3.4 Database Cyber System Architecture

3.3. Cybernetic Integrated Manufacturing Management System

To be applicable, CPS must include a system that allows the organization-reorganization of manufacturing system according to performance and objectives. In its evolved form, the cybernetic integrated manufacturing management system (MESI), integrates automated manufacturing management system capabilities which added elements that allow separation between passive and active resources of the CPS (157), provides the tools for defining and managing the CPS, the synchronous and asynchronous cybernetic subsystems, the manufacturing holons and information and communications management. The MESI is a platform where the basic functions are grouped in the form of a succession of applications that describes design procedure of the CPS. This platform covers the requirements of operational management, and the modular structure ensures scalability, flexibility and support for the integration.

3.3.1. Object management application developer

It is a programming application where digital copies of manufacturing resources and assets are defined. The programming environment must allow the definition of objects and operating submodels, both as digital representation objects and the different instances in which the manufacturing asset is involved. Object management software application describes any entity that has the quality of an asset of the manufacturing system, physical or digital.

The goal is to include these submodels in the AIAOC description of the evolution of quality parameters in relation to the processes executed.

3.3.2. Information and communications system developer

It is an application that aims to integrate hardware and software entities to ensure a continuous cybernetized manufacturing data flow, real-time data processing, and communication compatibility between the CPS and the production system. This results in an information network capable of managing the manufacturing execution, providing implementing control capabilities, and coordination between CPS subsystems. A special section is the SCADA component of CPS.

To acquire data, the set of signals, alarms, events and messages is defined in this section. The SCADA section also manage signals generated by the CPS, and organize signals, define and evaluate CPS actions when detect non-compliant values.

3.3.3. Cyber-physical system programming application

It is an application that allows digital copy modeling of the manufacturing system , based on asset management computer applications (AIAO). Also, allows manufacturing holons design by selecting the processes modules included in AIAO.

In order to sense the environment and initiate adaptive actions, the CPS holon must be connected to the digital structures that provide the cognitive and intelligence capabilities. This is achieved by connecting the AIAO modules to the entities that collect data at the physical level, interpret and communicate them to the holon. The connection is made between the AIAO and the function blocks of cybernetic objects defined at the SBDI level.

Once defined, holons are saved as executable applications and will be accessed on each manufacturing request. These holons also constitute manufacturing services.

3.3.4. Manufacturing execution management application

This application takes production orders (type of product, batch size and manufacturing term), selects the manufacturing resource (manufacturing holon), planning manufacturing, applies it, executes control and intervenes to adapt the entire system when the need arises.

The complexity of this application can increase depending on desired supervision control, and can be connected to analysis and evaluation tools, from where it can take information, estimates behaviour and publish for visualization on HMI displays.

The manufacturing manager can include several sections through which it presents real-time information about machines, batch manufacturing , products executed quality and communicate KPI's.

3.4. Cybernetic integrated predictive control system

Model Predictive Control (MPC) is the appropriate solution for an industrial application for cybernetic integrated manufacturing system due to spreading of this algorithm in control engineering. The predictive control model uses a process mathematical model representation to predict future system behaviors and to apply a control sequence for real-time optimization of the supervised process.

Programming MPC begins by defining the automated manufacturing system linear model in order to identify the descriptive function of system state space model and control variables.

Experimentally, a relationship is identified between input and output variables values, which best describes the process, as sum of effects of the input and output variables on the state of the system.

This model is an approximate system representation, used to discretizing the continuous model by applying a transformation function.

To formulate predictions, MPC requires to calculate a dynamic control matrix (MDC) to determine the variables evolution that describes the system state at future instances to update the internal state and achieve the state stability.

The MDC results are taken over by the MPC which will perform calculations for the mathematically modeled system, described by the two state equations:

$xm(k+1) = Amxm(k) + Bm(k) + Bd\ \omega(k)$

$y(k) = Cmxm(k)$

In this way, the behavior prediction values for the next instance are obtained.

These calculations are reported to the system constraints and are compared with the predicted values of the measured variables. The reference point optimization is done by determining the optimal command and control variables values, so that the objective function is fulfilled.

3.5. Research on reaction injection molding predictive control

The Reaction Injection Molding (RIM) process is used in the polymer industry to produce plastic parts. This process is based on the chemical reaction between two or more liquid monomers to obtain a polymer with different physicochemical characteristics. The most commonly used raw materials for this process are isocyanate and polyol, and the polymerization reaction produces polyurethane.

The reactive injection molding process includes the following steps: the dosing pumps take the two monomers from the tanks, in the quantitative ratio required by the manufacturing recipe, which they send to the mixing system. In this system, the reaction environment is provided, and the polymerization process parameters are managed by the control system (159).

The predictive control application will be designed for a plant that simulates this process. The objectives of the installation realization are to simulate the complexity and dynamics of the real installation, and the objective of the application is to manage the simulated process (see Fig. 3.5).

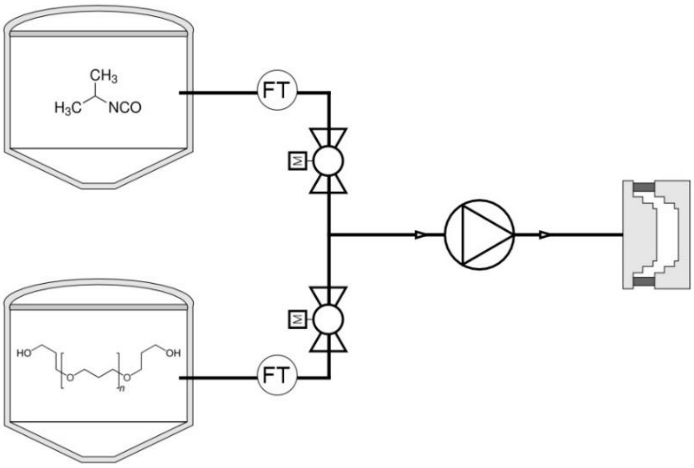


Fig. 3.5 RIM simulation plant representation

The predictive control application must manage the simulation installation. MPC programming must describe the dynamics of fluid flows, calculate the evolution prediction of internal state and formulate the feedback.

The objective of the MPC algorithm is to calculate the optimal value for each input variable, to ensure a precise composition at the output (55% isocyanate and 45% polyol), adjusting in real time the actuators position based on the feedback from the sensors, in order to achieve a system stability in the time horizon associated with manufacturing cycle. The first step in developing the application is to establish the parameters for the simulation:

```
T_s = 0.1; sampling period
T_sim = 50; simulation period
time = 0:T_s:T_sim;
```

The next step is system mathematical modeling, who begins by conducting an experiment in which the system variables values considered are measured. During the experiment, were recorded the following values :

State variables:

```
x_izo = [0 0.009 0.018 0.026 0.031 0.035 0.039 0.043 0.046 0.046 0.046]; isocyanate quantity
x_pol = [0 0.003 0.007 0.013 0.021 0.027 0.032 0.035 0.038 0.038 0.038]; polyol quantity
x_ame = [0.000 0.750 0.720 0.667 0.596 0.565 0.549 0.551 0.548 0.548 0.548]; isocyanate used in recipe (percent)
```

Command variables:

```
u_izo = [0.00 0.78 1.57 2.26 2.70 3.04 3.39 3.74 4.00 4.00 4.00]; controlling valve signal (isocyanate )
u_pol = [0.00 0.32 0.74 1.37 2.21 2.84 3.37 3.68 4.00 4.00 4.00]; controlling valve signel (polyol)
u_pompa = [0.00 0.57 1.19 1.86 2.48 2.95 3.38 3.71 4.00 4.00 4.00]; frequency converter signal (pump)
```

Control variables

```
y_izo = [0 0.009 0.018 0.026 0.031 0.035 0.039 0.043 0.046 0.046 0.046]; isocyanate flow rate
y_pol = [0 0.003 0.007 0.013 0.021 0.027 0.032 0.035 0.038 0.038 0.038]; polyol flow rate
y_total = [0 0.012 0.025 0.039 0.052 0.062 0.071 0.078 0.084 0.084 0.084]; total flow
```

Also, it is necessary to define variable constraints regarding plant operating limits, which will be used to manage the system:

```
xmin_ext = [xmin_izo_ext; xmin_pol_ext; xmin_ame_ext];
xmax_ext = [xmax_izo_ext; xmax_pol_ext; xmax_ame_ext];
umin_ext = [umin_izo_ext; umin_pol_ext; umin_pompa_ext];
umax_ext = [umax_izo_ext; umax_pol_ext; umax_pompa_ext];
ymin_ext = [ymin_izo_ext; ymin_pol_ext; ymin_total_ext];
ymax_ext = [ymax_izo_ext; ymax_pol_ext; ymax_total_ext];
```

Acording to experimental values, MPC will determine the elements of continous system. First step is to calculate variables gain values, witch will be used to determine the matrices for each variable.

```
K_x = [0.5, 0.3, 0.8];
K_u = [0.4, 0.35, 0.6];
K_y = [0.45, 0.33, 0.7];
A_x = cell(1, length(K_x));
B_x = cell(1, length(K_x));
C_x = cell(1, length(K_x));
D_x = cell(1, length(K_x));
```

Next, will be applyed the transfer function, in order to determine the matrices of the entire simulated RIM system:

```
for i = 1:length(K_x)
  sys_tf_x = tf(K_x(i), [T_x(i) 1]);
  [A_x{i}, B_x{i}, C_x{i}, D_x{i}] = tf2ss(K_x(i), [T_x(i), 1]);
end
```

```
A = blkdiag(A_x{:});
B = blkdiag(B_u{:});
C = blkdiag(C_x{:});
D = blkdiag(D_y{:});
```

By discretizing the system, the MPC calculates the elements necessary to achieve predictive control. The first step is to establish the reference trajectory of the state variable to obtain a stable system (see Fig. 3.6):

```
sys_continuu = ss(A, B, C, D);
sys_discret = c2d(sys_continuu, T_s, 'zoh');
[A_d, B_d, C_d, D_d] = ssdata(sys_discret);
w(w > 0.55) = 0.55;  Reference value
```

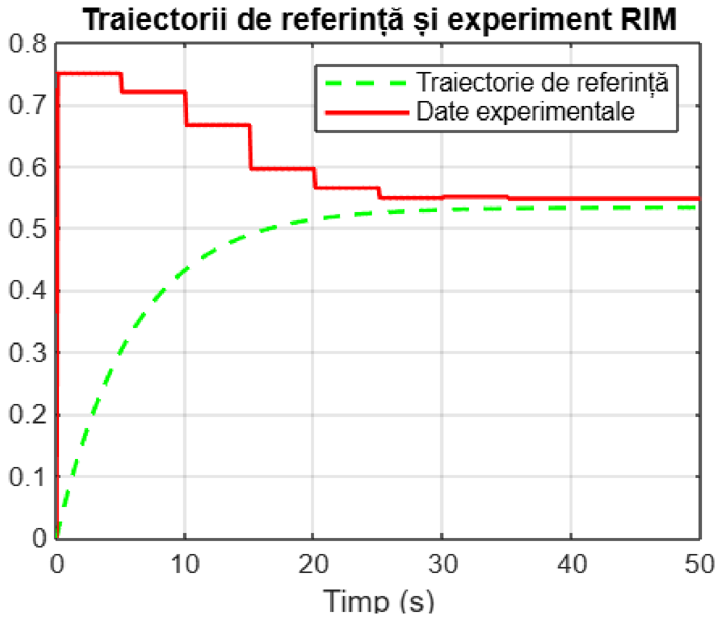


Fig. 3.6 Experimental and reference trajectories of the simulated RIM system

The next step is to establish the coordinates of the model's action:

```
N_p = 50 Prediction horizon
N_c = 9   Control horizon
x_ext0 = [0; 0; 0]; Initial system state
x = x_ext0;
N_sim = length(time)
n_inputs = size(B_d, 2)
```

To achieve predictive control, it is necessary to establish the objective function. The objective function aims to minimize a cost function. In this case, reducing the difference between the output variable and the reference value corresponding to the instance at which the calculations are performed. For this, MPC uses two matrices that penalize the deviation between the values of the output variables and the values of the control variables, matrix Q (deviations from the reference values), and matrix R (magnitude of the control variables).

```
Q_base = C_d' * C_d;
R = diag([0.01, 01, 0.001]);
for k = 1:N_sim
r = w(k);  Referința curentă (la momentul k)
e = (r - C_d * x);  Deviația față de referința curentă
```

To programming controller, two matrices are defined, the Hessian and the gradient, which direct the system towards minimizing the deviation from the reference trajectory. Thus, the system is driven towards an optimal solution, within the control horizon.

```
H = zeros(N_c * n_inputs, N_c * n_inputs);
F = zeros(N_c * n_inputs, 1);
for i = 1:N_c
H_block = B_d' * Q * B_d + R;
row_start = (i-1) * n_inputs + 1;
row_end = i * n_inputs;
H(row_start:row_end, row_start:row_end) = 2 * H_block;
F((i-1)*n_inputs+1:i*n_inputs) = (C_d * A_d^i * x - r)' * Q * B_d;
end
H = (H + H') / 2;
```

Once established, the controller calculates the optimized command variables, taking into account the constraints.

```
u_opt = quadprog(H, F, [], [], [], [], umin_ext, umax_ext);
u_opt_step = max(umin_ext, min(umax_ext, u_opt(1:n_inputs)));
y_opt = C_d * x + D_d * u_opt_step;
y_opt = max(ymin_ext, min(ymax_ext, y_opt));
x_opt = max(xmin_ext, min(xmax_ext, A_d * x + B_d * u_opt_step));
```

At each iteration, these updates are performed by the controller, within the prediction horizon. Applying the controller commands causes the managed system to behave close to the reference trajectory, corresponding to a stable system (see Fig. 3.7).

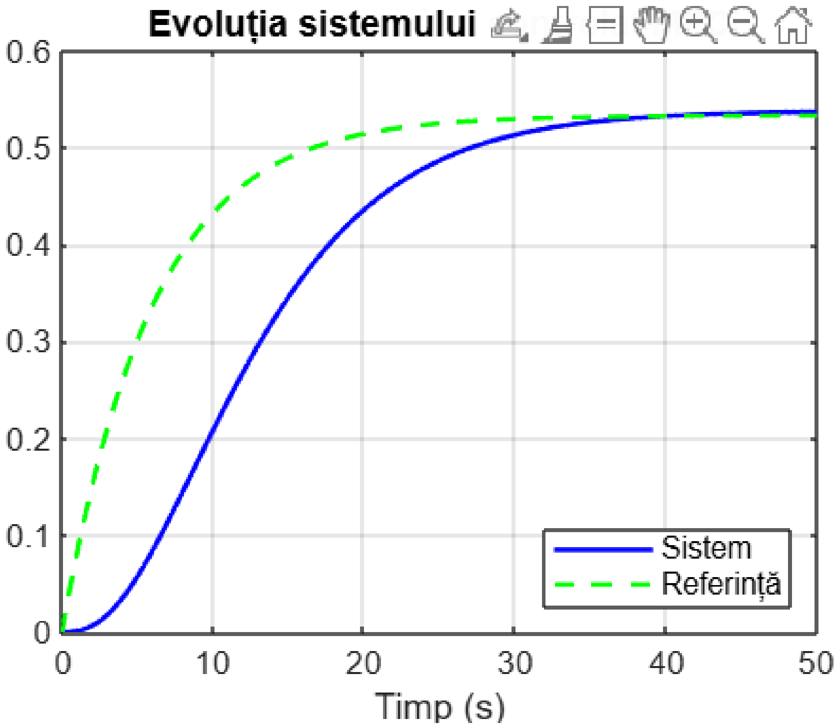


Fig. 3.7 Simulated system behavior, controlled by MPC

The plot describing system optimal evolution, according to reference trajectory, towards the steady state of the manufacturing process.

MPC algorithm is designed as a predictive cybernetic integrated control system, which allows the reconfiguration of CPS and mapping data according to manufacturing task for the algorithm will run predictive optimization calculations.

The flexibility, as well as the extensive applicability of predictive control models, allows the development of control solutions intended for a manufacturing asset or the entire manufacturing system, related to the process carried out by the computer-integrated manufacturing system.

3.5.1. Strategy of cybernetic integrated predictive control system

Model predictive control allows the abstraction of real elements in mathematical terms. In this way, the physical manufacturing system is mathematically represented in a model to which a solution for a problem is applied.

The industrial implementation strategy of the predictive control model is carried out at cyber subsystem level, and the flexibility of MPC provides the integrated platform that uses mathematical modeling. The MPC is localize in the asynchronous cybernetic subsystem, at the AIAO corresponding to the managed assets, and the predictive control system is an application of the synchronous subsystem of manufacturing processes, for each manufacturing holon (see Fig. 3.8).

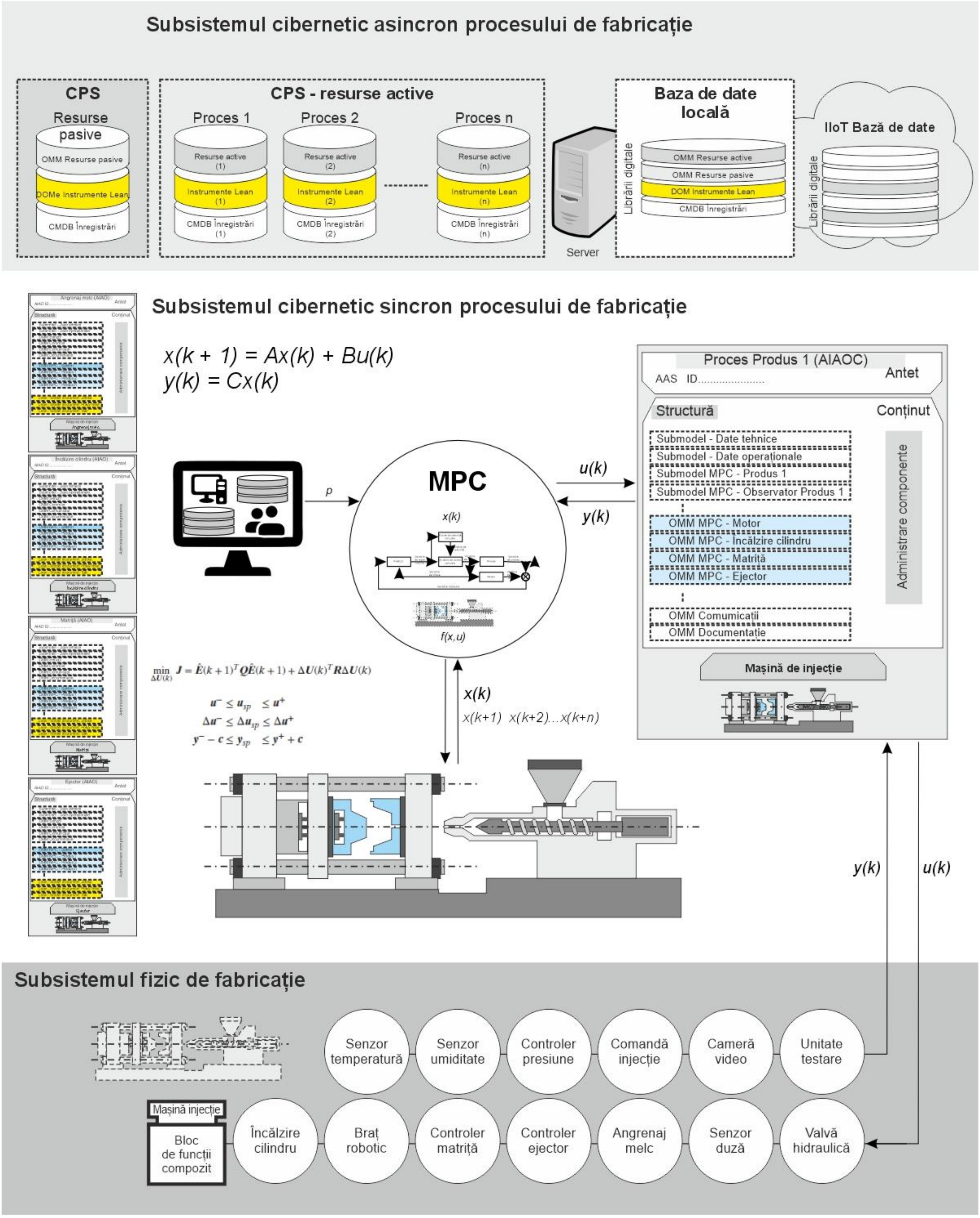


Fig. 3.8 Predictive control system integration

3.6. Strategy of cybernetic integrated lean manufacturing system

The cybernetic integrated lean manufacturing system (CPLS) is an cyber physic manufacturing system, whose elements are autonomous, self-configurable and in which the processes are carried out completely automatically. The applicable CPLS tools are digitalized, benefit from advanced manufacturing technologies, and their implementation aims to comply with principles of lean manufacturing.

The CPLS tools collect real time information from synchronous cybernetic system, formulate decisions, and applied correction commands at the AIAOC that runs the manufacturing scenario. The CPLS tools are grouped as a layer between the physical manufacturing system and the cybernetic one and individualize each stage of the manufacturing process. In this way, the manufacturing cell is transformed into a lean cybernetic integrated manufacturing system by updating physical active components, and at the cybernetic level – by initializing the corresponding digital elements, planning production processes, as well as activating the AIAL modules for supervising the manufacturing cell performance (157).

3.6.1. Poka-Yoke lean cyber tool

In the manufacturing process, the quality of polymer products is conditioned by a complex set of factors, starting from raw material preparation to storage finished product. The product quality measurement and evaluation is carried out by ensuring optimal parameters for final product. The purpose of these measurements is to identify errors (Poka-Yoke or mistake proofing) and to reduce losses by eliminating the causes that lead to waste (160).

The built-in quality control are specified into AIAOC modules of the injection machine, by summing the submodels. For additional equipment, the definition of Poka-Yoke is done through its own AIAL, in the same way. These models will manage the interaction between the physical components and the corresponding manufacturing processes, generating requests for adjustment of the manufacturing processes and correction of the operating parameters, which will issue work instructions that will be applied to actuators through function blocks (160) (see Fig. 3.9).

In this way, quality control procedures are applied at the manufacturing cell level, parameters are checked, deviations are corrected, and non-conforming products are selected and eliminated.

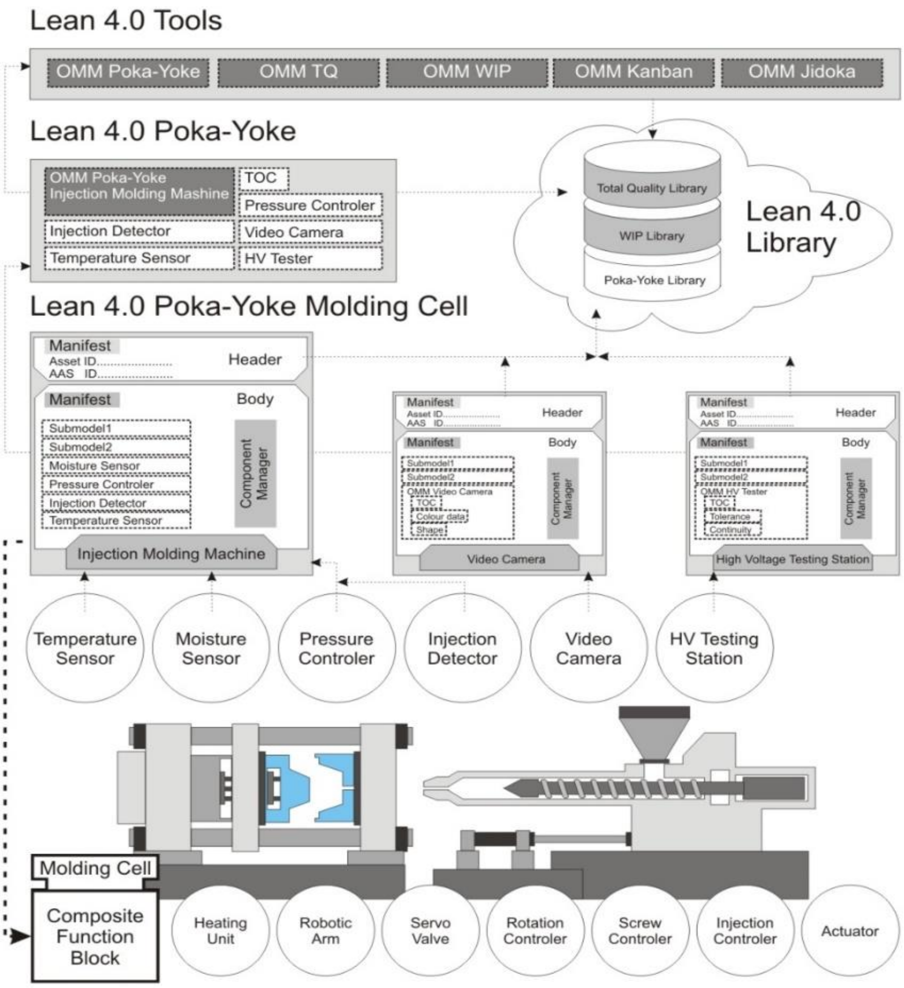


Fig. 3.9 Poka-Yoke Tool (160)

3.6.2. Cybernetic integration of Lean Management principles

To become lean, the CPS must apply Lean principles and integrate CPLS tools at the level of the synchronous subsystem, requiring a cybernetic structure in a coordinating position of physical and cybernetic holons. Similarly, the representation of the CPS through the AIAO, as well as defining cyber-physical holons as AIAOC, the CPSL is defined by Lean tools (AIAL) and tool groups (MAIAL). The two cybernetic structures, AIAOC and MAIAL, allow an adaptive manufacturing system, capable of supervising the processes, who generate events for each Lean tool and for the manufacturing processes included in the HCF. The MAIAL cyber subsystem is positioned within the CPS in a coordinating position of AIAOC, taking over the cyber system by applying Lean principles, to monitor flows and processes and to measure performance (161).

In this way, the information structure is distributed and subsequently archived in databases and storage media, internal or external to the asynchronous cyber system (162) (see Fig. 3.10).

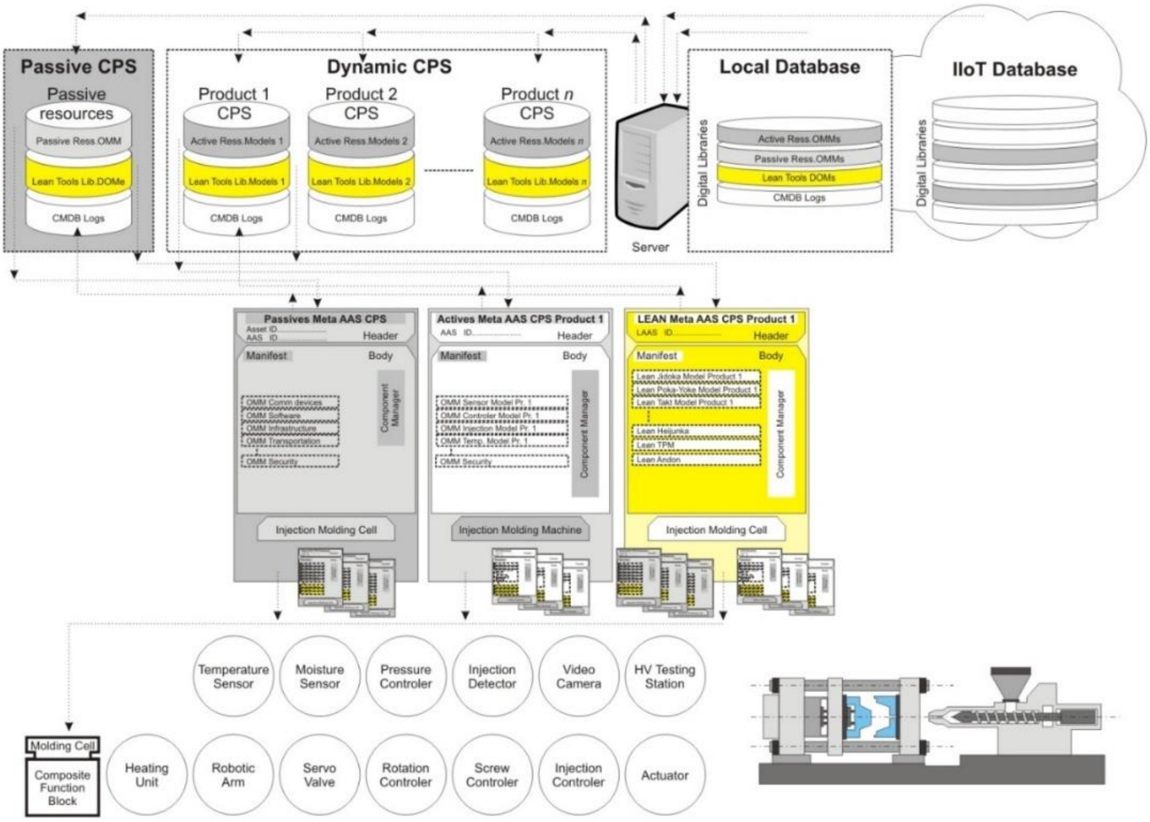


Fig. 3.10 Lean cyber-physical system (162)

4. Conclusions

The newest concept of smart manufacturing is based on the integration of information technology capabilities in the entire production system, which has led to a high level of interoperability and interaction between the system and its environment. Through cybernetic integration, the manufacturing system becomes intelligent, the system environment allows fully automated, digitalized and self-configurable manufacturing, in which the value chain is presented in a decentralized network whose elements are autonomous.

The actual stage highlights the attention of achieving flexibility, scalability and adaptability of the entire manufacturing system, according to the Industry 4.0 concept, by identifying the physical and cybernetic resources, and the capabilities necessary for the system to become predictive, in order to achieve integration of component subsystems (horizontal), of production and service systems (vertical) and to the value chain (in depth).

The study conducted has led to the following conclusions:

C1. The concepts of intelligent manufacturing system, integrated computerized manufacturing system and holonic manufacturing system identify theoretical solutions for cybernetic integration.

C2. Advanced manufacturing and communication technologies provides the necessary capabilities to define the cyber physical system, according to the concept of intelligent manufacturing.

C3. Newest technologies ensures advanced manufacturing management concepts, including agile manufacturing, lean manufacturing, adaptive automation and six sigma.

C4. Transformation strategies must take into account the type of technologies that support the manufacturing system cybernetic integration. These are computing and communication technologies, cyber-physical system implementation, large databases, algorithm implementation, virtualization of manufacturing processes and assets.

C5. The strategies tactics must aim to achieving an intelligent, dynamic, flexible, adaptable and connected manufacturing system, as well as defining manufacturing services.

C6. The strategy for achieving the cybernetic integration must dissociate between basic technologies, which allow connectivity and interaction with environment, and the support technologies, which provide necessary capabilities to transform physical systems into intelligent subsystems.

C7. The intelligence of cybernetic manufacturing system is based on a modular architecture, whose elements become autonomous. The necessary capabilities are obtained by implementing algorithms through which evolution and performance of manufacturing assets, processes and the entire system is managed. Whitin the cybernetic integrated manufacturing system, the algorithms play the role of a predictive control system.

C8. The computer integration strategy of the manufacturing system is developed into a set of subsequent strategies, corresponding to manufacturing assets integration, database system definition, implement the manufacturing management system and the predictive control system.

After cyber-physical manufacturing system implementation, by adoption of lean manufacturing principles and tools the cybernetic integrated lean manufacturing system will be achieved.

5. Personal contributions

The transformation strategy follows an cybernetic integration project in which subsystems are updated with advanced technologies.

CO1. The strategy assure necessary stages for realize the cyber-physical system by adopting advanced manufacturing technologies, integrating adaptive control algorithms, as well as computing and communication technologies.

CO2. Structuring the cybernetic system into two subsystems, according to the functions they must perform:

- Cybernetic asynchronous manufacturing processes subsystem - to providing a superior processing platform, used to define the physical manufacturing holons.
- Cybernetic synchronous manufacturing processes subsystem - to represent physical structures and manufacturing processes.

CO3. Defining physical system into two subsystems, according to the coresponding roles, by separating the elements actively involved in manufacturing processes from the passive ones, which do not change when changing from one manufacturing scenario to another.

CO4. Describing the information subsystem architecture according to the specificity of the two cybernetic subsystems.

- The IT&C network of the synchronous cybernetic subsystem, who ensures the holons implementation and communication between physical devices or equipment.
- The IT&C network of the asynchronous cybernetic subsystem, who accumulates the advanced technologies capabilities integrated to cybernetic manufacturing system.

CO5. The Integrated Information Database System is an information structure needed to digital integration of machines, equipment, human resources are stored, and data about raw materials, products and processes are stored to become available for further processing. The architecture describes the distribution of information about manufacturing resources, processes and products. The Integrated Database System is managed by an application through which modules are developed to be integrated into the management application cyber-physical manufacturing system.

CO6. Integrated manufacturing management system architecture described allow cybernetic control of automation and provide a flexible and scalable platform. The management platform is modular and flexible, incorporates digital tools to control the complexity of the manufacturing system, and basic functions are grouped in the form of a sequence of applications.

CO7. Defining the cybernetic integrated predictive control system as evolved form of the model predictive control algorithm, with the objective to providing a flexible and scalable platform, which allows the integration of evolved algorithms.

CO8. Description of the strategy and process for design, develop and implement of predictive control, as an intelligent solution for system and manufacturing process management.

CO9. I have developed a predictive control application for a simulation plant for a reactive injection molding process that highlights the algorithm's ability to manage and update behavior according to an objective function and constraints.

CO10. Defining the cybernetic integrated lean manufacturing system, where tools and principles of leanmanufacturing are digitalized and coordinate and supervise the manufacturing processes.

CO11. Strategy for defining the Poka-Yoke tool for a cybernetic integrated manufacturing system, where, by distribute through the manufacturing cell, quality control procedures are applied, parameters are checked, deviations are corrected, and non-conforming products are selected and eliminated.

CO12. Strategy for applying Lean Management principles in the architecture of the cyber-physical system, which connects the synchronous and asynchronous cyber subsystems, coordinates them, supervises the processes and applies corrections.

CO13. I have published five scientific papers in which I addressed the cyber integration of lean manufacturing systems.

6. Further research proposals

The strategy described offers a solution for cybernetic integration of manufacturing system, defining the cyber-physical system and a management architecture to design, implement and manage manufacturing processes. The thesis conclusions require further research to improve the identified solution.

In this regard, i have identified and propose the following research directions:

DC1. Identifing implementation procedures for adaptive, cybernetic integrated production system.

DC2. Develop an application for intelligent, cybernetic integrated production system.

DC3. Application architecture for the cyber-physical system

DC4. Identify an intelligent management process for cybernetic integrated manufacturing plant.

DC5. Research of complex management applications for hybrid algorithms.

DC6. Research on complex objective function structure of the predictive control system.

DC7. Research on predictive control matrices in learning processes, specific to cybernetic integrated manufacturing systems.

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