A control architecture for continuous production processes based on industry 4.0: water supply systems application

Edgar Chacón[1] · Luis Alberto Cruz Salazar[2,3] · Juan Cardillo[1] · Yenny Alexandra Paredes Astudillo[4]

Abstract

Industry 4.0 (I4.0) brings together new disruptive technologies, increasing future factories' productivity. Indeed, the control of production processes is fast becoming a key driver for manufacturing operations. Manufacturing control systems have recently been developed for distributed or semi-heterarchical architectures, e.g., holonic systems improving global efficiency and manufacturing operations' reactiveness. So far, previous studies and applications have not dealt with continuous production processes, such as applications for Water Supply System (WSS), oil refining, or electric power plants. The complexity of continuous production is that a single fault can degrade extensively and even cause service disruption. Therefore, this paper proposes the Holonic Production Unit (HPU) architecture as a solution to control continuous production processes. An HPU is created as a holon unit depicting resources in a continuous process. This unit can detect events within the environment, evaluate several courses of action, and change the parameters aligned to a mission. The proposed approach was tested using a simulated model of WSS. The experiments described in this paper were conducted using a traditional WSS, where the communication and decision-making features allow the application of HPU. The results suggest that constructing a holarchy with different holons can fulfill I4.0 requirements for continuous production processes.

Introduction

Water Supply Systems (WSS) are part of the critical infrastructure systems of a city or region aimed at satisfying the population's demand for water. They are Systems of Systems (Joannou et al., 2019), geographically distributed in networks. The use of technology is essential to manage kinds of net systems (Nam and Pardo, 2011). Those networks are autonomous nodes, having control procedures according to the function of the node. However, each node must cooperate with other nodes in order to accomplish a global objective.

✉ Edgar Chacón
echacon@ula.ve

✉ Luis Alberto Cruz Salazar
luis.cruz@tum.de

1 Universidad de Los Andes, Mérida, Venezuela

2 Universidad Antonio Nariño, Bogotá, Colombia

3 Technical University of Munich, Munich, Germany

4 Pontificia Universidad Javeriana, Bogotá, Colombia

Those systems are considered as a System of Systems (Colombo et al., 2019). The WSS is a set of continuous processes with jumps that are necessary to respond to changes in water supply and consumption, restrictions on pumps and valves, and also for failures in pipes and equipment.

This paper proposes an Holonic Manufacturing Systems (HMS) that integrates the physical level with the enterprise level allowing the execution of processes associated with operation management. The HMS can make configuration, reconfiguration of physical processes as results of the scheduling activities, and the supervision tasks to ensure the established WSS goals. The HMS aim to decentralize the manufacturing tasks into individual decisional entities (i.e., holons) for featuring autonomous, cooperative, and responsiveness behavior within manufacturing operations (Pujo et al., 2009). Therefore, the development of the holon concept and the holarchy organization has become a central issue responding to the efficiency and the reactive manufacturing challenges. Besides some HMS contributions (Chokshi and McFarlane, 2008b; Indriago et al., 2014; Bloch et al., 2017), have tended to focus on intermittent and discrete

processes, rather than continuous production processes e.g., chemical processes, WSS or oil refining processes (Chokshi and McFarlane, 2008a).

The implementation of the proposed architecture is called Holonic Production Unit (HPU), as given in (Cruz S. et al. 2019). An HPU is divided into three levels: Plant level, where physical processes (mechanical, chemical, biological) take place; operations management level, aimed at optimizing the production process; and the business level. The plant level has a traditional architecture based on PLC (Programmable Logic Controller) and its SCADA (Supervisory Control and Data Acquisition). Therefore, this level contains a regulatory control tasks, and a local supervisor works together for monitoring the system sensors (i.e., water storage, tank level, water treatment rate, among others). The Image level, similar to the Digital Twin concept, contains the HPU's information that allows supervising negotiating, retrieving/storing data, and interacting with other HPUs. These contribute to maintaining the state and evolution of the physical process. The enterprise level, as a non-real time regulator, it is oriented to evaluate the execution, transfers information to the enterprise systems, and accepts/rejects the assigned objectives and to establish cooperation with customers and suppliers.

After a brief introduction highlighting the complexity of WSS management and its automation, this document is organized as follows: "Water supply systems: a brief description" section describes the structure, functions and general behaviour of a WSS, the aspects of process integration, and the Information Technology (IT) and Operation Technology (OT) in this architecture. "Literature review: intelligent automation systems addressing I4.0 requirements" section describes a literature review addressing the I4.0 needs in manufacturing, and the trends that allow the integrated automation of the different processes by Intelligent Manufacturing Systems. A description of the HPU and its formal basis is given in "Automation approaches meeting I4.0 requirements" section. "Mission Holon (MH)" section describes the technological architecture of the HPU. In "The human in the loop" section the methodology for the application of HPU in WSS is shown. "Deploying the Holon over the IT/OT technology" section analyzes the fulfillment of the I4.0 requirements exposed to the HPU, and final conclusions are given in "The bottom layers of the HPU and the OT" section.

Water supply systems: a brief description

The urban water has a cycle that covers from the water catching process until the devolution to the environment, and by evaporation returns as surface water or groundwater to the

rivers and aquifers (Marsalek et al., 2006), as is shown in Fig. 1.

A WSS make part of the urban water cycle and connects units for collecting, storing, transporting, purifying, distributing drinking water to the population of a geographical area, particularly cities. WSS has an organization that allows to accomplish the objectives in supply water to the population, maintaining economic viability and sustainability with the environment. A WSS may have several sources (superficial and groundwater), several purification units, a main network that take the water to the distribution tanks and the secondary distribution networks.

The WSS enterprise organization

Figure 2 shows a functional breakdown of the technical processes associated with the supply of drinking water from collection, distribution and recovery to return to the environment. Specialized units carry out: (a) the collection of water from different sources, (b) the management of purification and distribution operations and, (c) the management of users that characterizes them, establishes their physical link to the network and analyzes their needs and ensures the interaction between customers and operations to detect supply anomalies. In addition, the maintenance unit guarantees the correct functioning of the resources.

Planning in a WSS covers two aspects: (1) the study of future demand and the construction or improvements of the infrastructure, and (2) the management of demand and production balances for the coming months ensuring the satisfaction of the population and the ecological consumption, generating projections of demand and raw water contributions to the system. A typical pattern for water demand and rains is shown in Fig. 3, and the variations of water consumption and their amounts for a city and a neighborhood are given in Fig. 4 (Candelieri and Archetti, 2014). Tanks, by
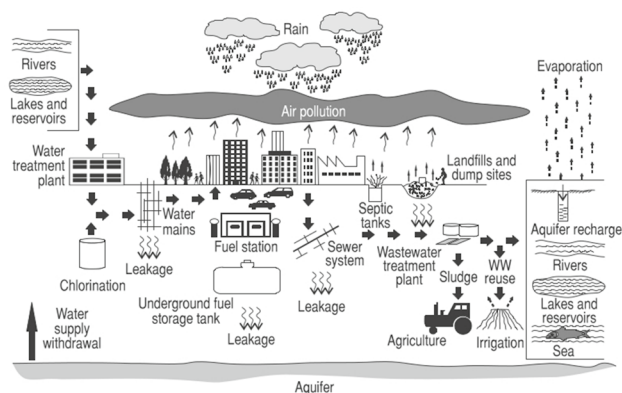

Fig. 1 Urban water cycle, from Marsalek et al. (2006)

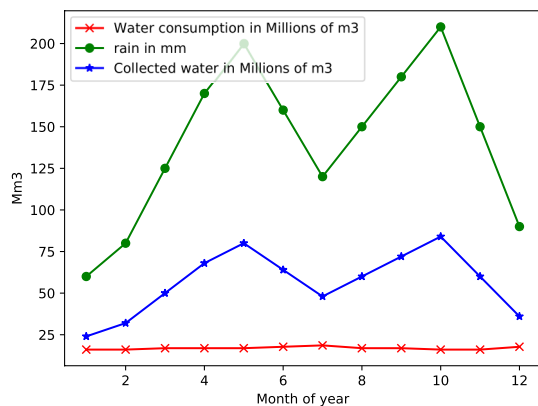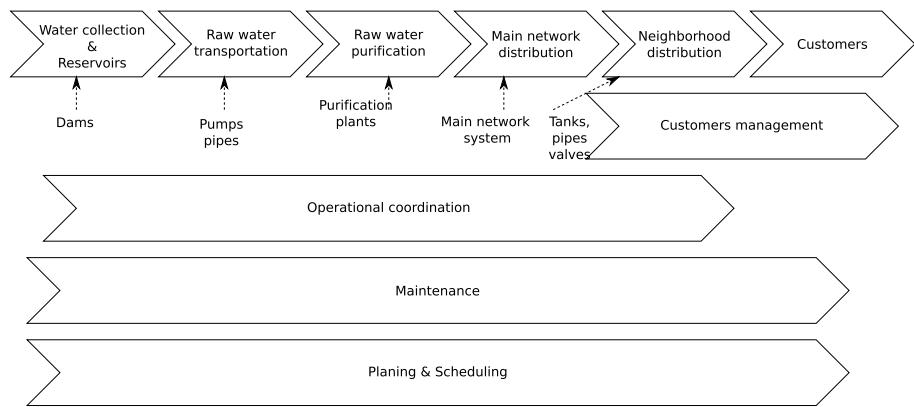**Fig. 2** Description for a hydrological enterprise (UML Eriksson—Penker diagram)

Fig. 3 Historical behavior of rains (green) collected water (blue) and monthly consumption (red)
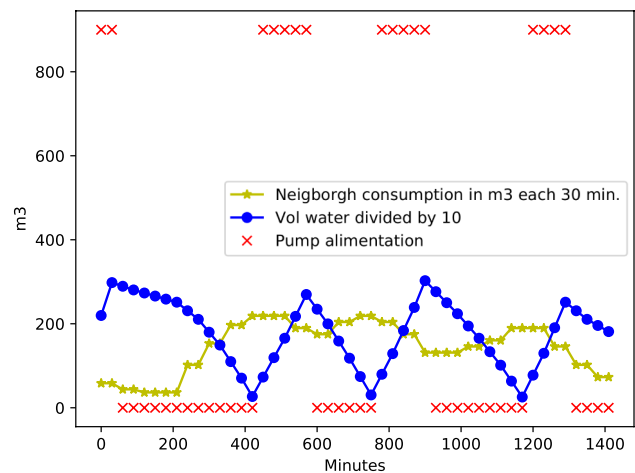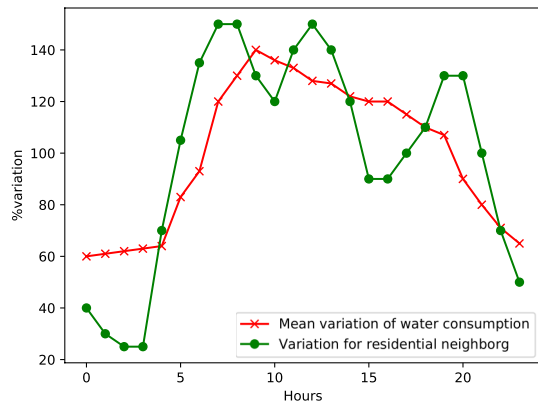

Fig. 4 Mean dairy consumption of a residential neighborhood and average consumption for a city (data from Candelieri and Archetti (2014))

design, are expected to store 33% of the daily consumption, and Fig. 5 shows the behavior of a distribution tank.

Fig. 5 Behavior of a tank for a neighborhood

IT integration for WSS: migration from the classic approach

For the effectiveness of the decision-making schemes, the following considerations must be taken: (1) In the management of the operation, at least the network models, generated mainly by the design department, the models of the infrastructure generated by their condition and resource behavior models that allow valid configurations to be established, (2) In the case of serious failures, the system must establish configurations to apply for contingency plans, prioritizing critical entities in the system, e.g., hospitals.

SCADA systems for managing operations in WSS are common in cities with more than 100,000 inhabitants. There are several providers of this technology such as Schneider, Siemens, etc. In principle, these systems are disconnected from administrative and longterm planning systems. Operations management and fault handling are basically done manually according to the experience of the operations personnel and in some cases guided by simulators. In the planning environment, the systems used are based on GIS

and hydraulic models based on the gradient method (Todini and Pilati, 1988), which is used in applications such as Watergems (Bentley) or Epanet (EPA), these applications have georeferenced information handy for operation and hardly seen a timid IT integration with SCADA (Li et al., 2020). The billing systems have the information necessary for the planning of operations, they are not connected with the planning systems, as well as the systems of operation scheduling and their information about the users is necessary for the establishment of network configurations. Such is the case, of a breakdown (failure), it is necessary to know which users are connected to which network, which is the priority to establish a path that ensures the supply of drinking water, possibly through a secondary network.

Hydrological Companies, with a high degree of development, have Information Technology (IT) infrastructure that support the planning of operations connected with administrative systems, and an Operations Technology (OT) infrastructure, based on the classic CIM approach as shown in Fig. 6, to manage production operations. New analysis based on the performance of analytical functions are incorporated to improve leak detection. Also, functions to support the management of interactions between maintenance and operation personnel to establish configurations when maintenance work is carried out, as well as to establish operation sequences when new network configurations are needed, but there is still no full integration (vertical, horizontal). Integration of all systems, with built-in insulation, is very difficult and in most cases not possible. That is why the holistic view of I4.0 reveals the required integration in WSS and the need to do so defines its feasibility.

Literature review: intelligent automation systems addressing I4.0 requirements

Origins of manufacturing systems until the modern I4.0 paradigm have correspondences with cognitive features of human behavior to get smart control (Galán et al., 2000). For
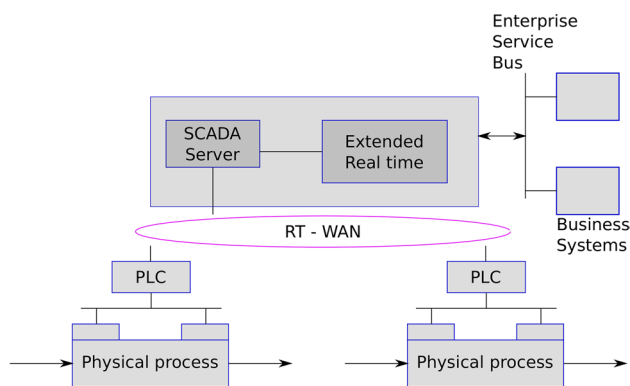
example, contemporary automation systems are addressed by distributed artificial intelligence from various perspectives, such us: Multi-agent Systems (MAS) (Leitão et al., 2016; Salvador Palau et al., 2019; Seitz et al., 2021), Services Oriented Architecture or SoA for manufacturing (Garc´ıa V. et al., 2013; Gamboa Q. et al., 2013), HMS (Leitão and Restivo, 2008; Hsieh, 2009; Borangiu et al., 2014; Valckenaers, 2020), HMS for continuous processes (Chokshi and McFarlane, 2008a; Chacón et al., 2009; Indriago et al., 2014), Cyber-Physiscal Systems (CPS) (Lee et al., 2020; Monostori et al., 2016). All of them are different approaches but they follow common requirements to archive the I4.0 paradigm, as introduced in the next sub-section.

3.1 WSS requirements established by Intelligent Manufacturing Systems for I4.0

HMS architectures contribute to the future challenges of I4.0 (Derigent et al., 2020). However for HMS to be aligned to I4.0 (Derigent et al., 2020; Ribeiro and Hochwallner, 2018; Vogel-Heuser et al., 2014), should fulfill five essential requirements (Req1-Req5). These are fundamental properties aligned with the I4.0 paradigm based on the *Cyber-Physical Production Systems* (CPPS) concept (Cardin, 2019). There is a list for *CPPS Minimal Conditions* identified and they are grouped into four main categories (Cruz S. and Vogel-Heuser, 2017): *CPPS minimal conditions (Req1), Smart characteristics attributes (Req2), Formalized Modelling Terms (Req3)*, and *Systems and Human integration needs (Req4)*. This contribution adds another requirement regarding the *Reference Architectural Model Industrie 4.0 "RAMI4.0"* (Plattform Industrie 4 0 2018). Table 1 summarises and adapts these requirements to address WSS, based on Cruz S. and Vogel-Heuser (2017).

Automation approaches meeting I4.0 requirements

The automation of continuous production systems evolve from the Mesarovic et al., (1970) hierarchical approach, the first approach manages the complexity of these systems. Difficulties in achieving models that represent reality make this approach shift towards decentralized systems (Brdy´s and Roberts, 1986) and later using hybrid systems to model such systems (Morari et al., 2003). Both approaches use continuous local controllers and coordination that can be based on discrete abstractions of piecewise continuous systems. This allows the decentralized management of production nodes in a networked system.

Since manufacturing systems challenge changes daily (Leitão et al., 2016), to meet complex needs, various architectures have been proposed (Borangiu et al., 2019). In general, these architectures range from hierarchical (e.g. CIM), with centralized decision-making schemes with a

Fig. 6 Classical IT/OT architecture for WSS

Table 1 Minimal requirements for Industry 4.0, addressing WSS. Adapted from (Cruz S. and Vogel-Heuser 2017)

Req1. CPPS Minimal conditions (Cruz S. and Vogel-Heuser 2017)	
Req1.i Independent architecture model	Implies that WSS's modules are simple to be integrated with open architecture and platform for independent implementations
Req1.ii Industrial IoT protocols	From the Industrial IoT concept, WSS are capable of offering easy cloud services
Req1.iii Follow ISA 95 Standard	WSS are available depending on the automation levels in which it will be applied
Req1.iv Smart Product	WSS are able to get usability and adaptability features to the water
Req2. Smart characteristics attributes (Cruz S. and Vogel-Heuser 2017)	
Req2.i Autonomy	WSS process owns experiences achieved by autonomy behaviors to achieve its goal
Req2.ii Open communication networks	WSS are capable of being easy and quick to switch between open networks
Req2.iii Cooperation	WSS develop mutually acceptable goals together other systems
Req2.iv Pro-activity	WSS are capable of achieving its assigned goal, avoiding unexpected situations
Req3. Formalized modelling terms (Cruz S. and Vogel-Heuser 2017)	
Req3.i Standard language for modelling	Fundamental modeling for the vertical expansion (among SCADA, MES and ERP)
Req3.ii Abstraction	Different degree of abstraction for applying various models in WSS
Req3.iii Integrated Development Envi-ronment (IDE) and platforms	Implementation of available tools for WSS development
Req4. Systems and human integration Needs (Cruz S. and Vogel-Heuser 2017)	
Req4.i Open systems to different sys-tems domain	Open WSS can interact with different systems domain, e.g., smart grids
Req4.ii Hybrid topologies	Need to enlarge or downsize the production of WSS
Req4.iii Social norms regarding human factors	WSS consider human behavior into their control loops
Req5. RAMI4.0 architecture features (Plattform Industrie 4 0 2018)	
Req5.i The "Hierarchy levels"axis	Axis for assigning functional models to specific WSS levels of hierarchy based on the IEC 62264–1 (ISA 95) and IEC 61512–1 (ISA 88) standards
Req5.ii The six "Layers" axis	WSS represent various types of data of the asset (cyber and physical resources)
Req5.iii The "Life-cycle" axis	WSS perform the lifetime of the assets and their value-added process

cognitive model at the higher levels of the hierarchy. Moving on to the heterarchical and semi-heterarchical (Trentesaux, 2009), with decentralized schemes where the cognitive model is now distributed (Jiménez et al., 2017). The last ones depend on the behavior, structure, and dynamics dispersed that are expected during smart manufacturing processes, i.e., by CPS, HMS, MAS, among others. Until the current evolution con-ceiving architectures with holonic philosophy self-organized in holarchies and whose main implementation is given by agents (Colombo et al., 2006), whose cognitive model is given in the holarchy, where each entity (holon) is autonomous - intelligent (Blanc et al., 2008; Barbosa, 2015; Dias-Ferreira et al., 2018). In the manufacturing processes this paradigm is known as HMS and they have two representative architectures: ADACOR (Barbosa et al., 2015) and PROSA (now ARTIS) (Valckenaers, 2020). Selected HMS that fulfil I4.0 requirements are compared in Table 2.

Holonic production unit architecture

Process industry, oil & gas production, energy generation/distribution systems, and WSS, among others, are systems that must guarantee a continuous flow of material to satisfy production demand. Those systems are constituted by a set of connected units (facilities, utilities, process units) forming a production network. Each Production Unit (**PU**) has its own behavior and the global behavior comes from the composition of local behaviors. Pipes give the connection between units where the material flow is continuous. Product flows in pipes is bulk and the material streams are transformed at the process units, adding value to the material until reaching the desired product. We will call PU to each process unit and also the transportation units area considered as PU. See Fig. 7.

Table 2 Comparison of selected HMS meeting I4.0 requirements (see "WSS requirements established by Intelligent Manufacturing Systems for I4.0" section)

| Authors	Scope	CPPS	Smartness	Models	Human	RAMI4.0
Valckenaers (2020)	HMS for Industry	−	+ +	+	+	−
Derigent et al. (2020)	HMS for Industry	+ +	+ +	−	+	+
Cardin (2019)	HMS for Industry	+ +	+ +	−	−	−
Barbosa et al. (2015)	HMS for Industry	+	+ +	+	+	−
Zapata (2011)	HMS for Industry	−	+ +	+ +	+	−
Giret and Botti (2009)	HMS for Industry	−	+	+ +	−	−
Indriago et al. (2014)	HMS for continuous processes	+	+ +	+ +	−	−
Chacón et al. (2009)	HMS for continuous processes	−	+	+	+	−
This paper's authors	HMS for continuous processes	+ +	+ +	+ +	+	+
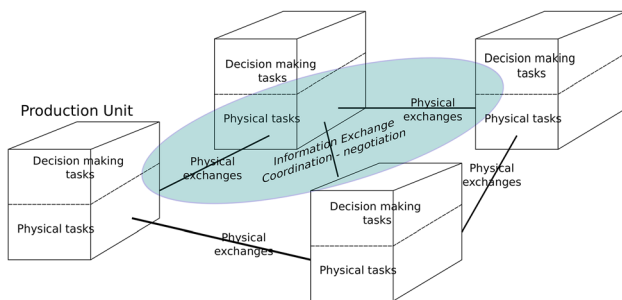
Fig. 7 Physical components (equipment) and the possible physical interconnections and the comunications network

Each PU has *internal resources* that must be managed to perform *production processes*. Processes at the PU have behaviors that must be controlled by means of controllers and supervisors. The necessary knowledge to ensure the right behavior of a process is stored internally at the PU. PU performs "*viable processes*" to achieve a goal, where goals are negotiated accordingly the internal capabilities. Then PU has the necessary knowledge to negotiate goals (missions). A complex goal can be obtained by a sequence of processes that can be internal to the PU or performed by a set of PU's. Then a PU that have all these capabilities is considered a HPU.

Implementing a concept for geographically distributed continuous process systems requires a geographic distribution of control equipment at the edge with the ability to execute control algorithms and the handling of equipment failures. In this case, a WSS requires high-speed connections to handle the interactions between physical processes and changing modes of operation. As a result, recent alternative projects for distributed and decentralized systems are given by the I4.0 paradigm. For instance, Colombo et al. (2019); Leitão et al. (2016), introduce SOCRADES and IMC-AESOP projects for SCADA and DCS, as mechanisms to develop CPS.

Modeling the behavior of the global system

Hybrid Dynamical Systems **HDS** (Lygeros et al., 2012) appear as a tool that facilitates the modeling and control of physical production processes through the sequencing of modes of operation. Here is the proposed HMS's relevance since the HPU has a considerable advantage over other approaches because they can be engineered as a holistic approach to suit different applications. The novelty focuses on continuous processes, where each mode of operation is represented as a discrete state. The global dynamics are represented as a sequence of operation mode jumps. The behavior of a production unit is described as a HDS, which has its own monitoring mechanism. Each discrete state of the production unit has its own control law that allows it to stay in that state or reach a target state. In behavioral modeling, a discrete state has a set of constraints on inflows, a set of constraints on outflows, and a control law to achieve or maintain the goal. Each discrete state is an abstraction of the continuous behavior of the controlled system, and it is necessary to have the event detection mechanisms that guarantee that the continuous dynamics is correctly mapped. Tazaki and Imura (2008) states that in the case of interconnected systems, the compound dynamics can be followed through abstractions if the requirements set out above are met. For a mode of operation of a subsystem the output flow must comply with a set of constraints that the receiving system of the flow knows in advance. Failure to comply with the restrictions implies that the HPU changes modes of operation and the receiver must change modes of operation. The discretization of each subsystem is associated with its outputs. Each subsystem is discretized separately.

An **HDS** is defined in several ways: as a Phase Transition Systems, as a Hybrid Automata (Lygeros et al., 2012), by means of Petri Nets (Lennartson et al., 2016) by Differential Logics (Platzer, 2010). We will use the definition given in (Lygeros et al., 2012) for a controlled general hybrid dynamical system.

A Hybrid Automaton *H* is a collection

$$H = (Q, \ X, \ f, \ Init, \ Dom, \ E, \ G, \ R)$$

where:

Q = {q1, q2, q3 .....} is a set of *discrete states*;
X = R^n is a set of *continuous variables*;
$f(\cdot, \cdot) : Q \times X \rightarrowtail R^n$ is a *vector field*;
$Init \subseteq Q \times X$ is a set of *initial states*;
$Dom(\cdot) : Q \rightarrowtail 2^X$ is a *domain*;
$E \subseteq Q \times Q$ is a set of *edges*;
$G(\cdot) : E \rightarrowtail 2^X$ is a *guard condition*;
$R(\cdot, \cdot) : E \times X \rightarrowtail 2^X$ is a *reset map*.

See (Lygeros et al. 2012) for the description of concepts such as *Hybrid trajectory, execution, reachable state, composability* that allows the construction of control & supervision mechanisms for the HDS. In our case, several process units that interoperate, the synchronization (cooperation between units) proceeds physically by the outflows exchange among units. In a similar way, for each discrete state, a regulatory control function is associated, and the transitions generate symbols that allow the tracking of the system by a supervisor.

The system's global behavior is achieved through the composition of the abstractions of the behavior of each subsystem. The hybrid model of each subsystem to meet the bisimilarity (Tazaki and Imura, 2008) requirements in order to be used in the construction of possible configurations.

The architecture presented assumes the existence of an intelligent resource. It is capable of negotiating a goal, in operation it executes control mechanisms to ensure compliance with the goal. Resources are honest, when a resource detect that the objective is not out of reach, it manifests it to the rest of the resources. In your operation, if you must cooperate with other resources, follow the agreed steps to synchronously achieve the objectives. Physically, the resources have a set of connections for the transfer of matter and energy that may or may not be enabled for a configuration. For a connection between two resources, in a configuration, the flows of matter and energy between them are previously agreed.

To arrive a configuration a negotiation must be performed to arrive to a schedule by using the bisimilarity concept; the negotiation determines the way to perform the coordination among the HPU and establishes the local supervisors. Each HPU presents the layers shows in Fig. 8.

Components of the Holonic Production Unit.

The PU has *internal resources* that must be managed to perform *production processes*. Processes at the PU have
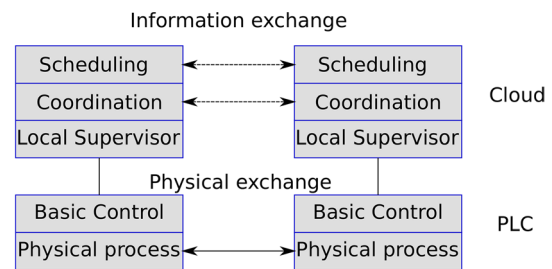

Fig. 8 Cooperative holons. Adapted from Chokshi and McFarlane (2008a)

behaviors that must be controlled by means of controllers an supervisors. The necessary knowledge to ensure the right behavior of a process is stored internally at the PU. PU's perform "*viable processes*" to achieve a goal, where goals are negotiated accordingly the internal capabilities. Then a PU has the necessary knowledge to negotiate goals (missions). A complex goal can be obtained by a sequence of processes that can be internal to the PU or performed by a set of PU's. If a PU those components is a HPU.

As in the ADACOR proposal (Leitão and Restivo, 2008), there are four main holons: (a) Mission Holon (MH) similar to the Order holon. (b) the Resource Holon (RH), in our case the central holon that performs both the physical tasks -equivalent to the Operational Holon in ADACOR- and the management tasks using the other two holons. The Engineering Holon (EH) that has the knowledge base of the product model and the behavioral models for each service provided by the resource, similar to the Product holon of ADACOR. The Supervisor Holon (SH), named the same as in ADACOR (Leitão and Restivo 2008; Barbosa et al., 2015), but derived from the concept of supervisory control of hybrid systems, which work on abstractions of continuous dynamics on the plant floor. These abstractions are built through Petri nets, and the interactions between the levels are given by messages associated with events. Therefore, even from different domains, our proposed HPU architecture differs from ADACOR mainly in the SH due to its decision hierarchy and the RH concept as the central element, not as the operational element (Leitão and Restivo, 2008).

The components of the HPU are given in Fig. 9.

The Engineering Holon (EH)

EH manages the production knowledge. The knowledge is grouped into three elements: (1) The Product Model, which describes the set of services provided by intelligent resources to obtain a product and its order of execution including the formula. (2) The Process Model, which is the
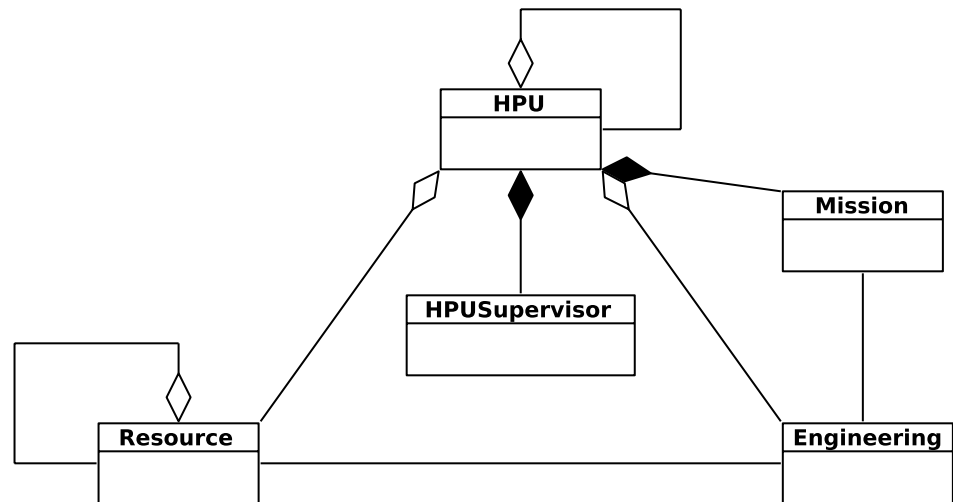
procedure used by an HPU to provide a service. (3) The
control mechanisms that ensures the right behavior of the
system for each process model and it will be employed by
supervisors to assure the accomplishment of goals.

Resource Holon (*RH*)

The physical system, as is shown in Fig. 7, is composed by
several units, where each unit performs the necessary tasks
in order to accomplish a *service*. The concept of service
(Karnouskos et al., 2012; Gamboa Q. et al. 2015) is used
to facilitate the description of the Product Model. A RH
is autonomous, that is, it is able to establish its own goals,
supervise and control its evolution. Each RH establishes its
goals by a negotiation process among the others RH in order
to achieve the global one.

RH is the central element in the architecture used. RH
manages its internal resources, and executes the physical
processes necessary to meet the production objective. RH
negotiates with other RH missions, establishes produc-
tion commitments, calculates the local supervisor to be
used to monitor, and control the mission. An HPU can be
a resource for another HPU more generic as is shown in
Fig. 9. To manage the internal processes the HPU is par-
titioned in several *resource layers* as is shown in Fig. 10.
The upper resource layers perform the negotiation with
other HPU. It evaluates the possibilities to accomplish its
part of the global goal and send an expected behavior to

evaluate the whole behavior. If the composition of the sys-
tem is considered viable, an agreement is achieved. Topo-
logical Models is the layout of the plant that describes the
equipment (PU) and its hierarchy and the interconnections
among the PU's; an information exchange model describes
the flow of data from the plant floor to the decision layers,
and a plant information model (PIM), as introduced by
Pérez et al. (2015).

Mission Holon (MH)

Similar to the Order Holon in PROSA (now ARTI by
Valckenaers, (2020)), and the Task Holon in ADACOR
(Leitão and Restivo, 2008), the MH has the objective to
be reached or maintained by a PU during a period, it also
has the information about the fulfillment of the mission.
Goals and State of the Mission are part of the MH. A
mission results from evaluating the feasibility of meet-
ing a production objective. If the objective is achievable
by the PU and a configuration is established, that means
an acceptation of the mission. For an accepted mission,
the PU creates a supervision mechanism to ensure the
achievement of the objective. MH and SH are strongly
coupled, since for each accepted mission a supervisor is
established. When the process is continuous or batch, the
evolution is described as a Hybrid System.

A mission has three stages:

- In Evaluation. At this stage the HPU receives a proposal to performs a service. The algorithm for evaluation of a mission is given in Algorithm 1.
- In Execution. It corresponds to the control system to ensure that each stage is performed as planned. The interaction between local supervisors and the global supervisor ensures the achievement of the mission. For continuous systems, the regulation is performed for each pass. At the execution the information of physical process and resources is collected to determine control signals and events that determine the evolution of the process.
- Completed Mission. At the end of the mission, resources are liberated and a evaluation of the performance for the mission is made, also an evaluation of the resources is made to determine the needs of maintenance.

Algorithm 1: Negotiation of the mission.

```
Data: Mission (Service), Network topology (PIM),
      HPU's
Result: Updated Plan
initialization;
if Service can be developed then
    Establish the set of possible configurations using
      PIM information;
    foreach conf in configurations do
        foreach unit in conf do
            ask for the abstract behavior of the
              resource;
            compose the global model;
        end
        Calculate the viability, performance;
    end
    Select the best configuration;
    Send the offer and the abstract behavior of the
      service or the rejection;
    wait for the acceptation;
    if offer accepted then
        Establish the local supervisor;
        Establish the coordination mechanisms;
        Update the plan;
    end
else
    Reject the solicited service
end
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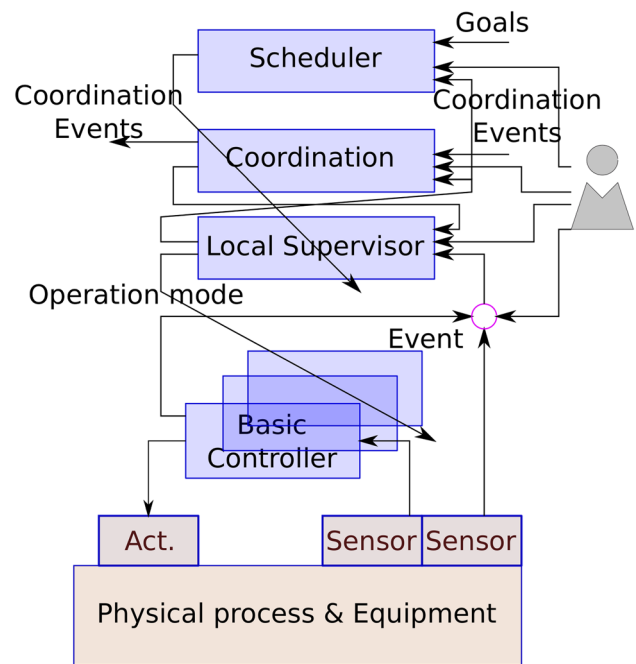

Fig. 10 Supervisory control levels in a Production Unit

Supervisor Holon (*SH*)

Harjunkoski, (2009) analyze the characteristics of production programming and process control and the need to integrate both tasks. The time scales at the two levels are different, and the programming decisions are discrete, while the control decisions are continuous. Discrete decisions determine the evolution of the dynamics on the plant floor, at the same time, that discrete decisions are conditional on the feasibility of continuous dynamics. In an HPU, the tasks of basic control, monitoring - supervision - coordination and planning occur simultaneously. Supervision can alter the dynamics of the floor by changing the operating mode, and in the floor, operating conditions can generate events that trigger the monitoring mechanisms. If supervision cannot find a suitable mode of operation, a reconfiguration mechanism is triggered. Coordination has two functions local internal coordination among the set of HPU that works in a configuration, and the cooperation mechanisms with other HPU. The local supervisors send events that allows to have updated the abstraction of the process. If the abstraction arrives to a non-desired state the reconfiguration process is

triggered to arrives to a new viable configuration. The integration of the decision levels is shown in Fig. 10.

In the continuous production process, each unit with autonomy can be seen as CPPS (Bloch et al. 2017). In execution, the HPU supervisor executes in Algorithm 2 to evaluate and ensure that the process behaves correctly.

The technological architecture: HPU's IT/OT

This section shows how the functions of the HPU must be projected on the platform of technologies of operation IT/OT available in the plant. For a classic infrastructure, like the one shown in Fig. 6, the regulation functions go directly in the PLC (often OT component), the supervision and coordination functions in the equipment in the non-strict real-time level, and the programming and planning functions in the IT level, which store knowledge and images (digital copies) of plant processes and equipment. These images of the process are the basis for determining the state of the system and generating the scheduling of plant floor activities and determine local supervisors and coordination mechanisms among the units.

Algorithm 2: Monitoring the process

Data: Network topology, HPU's Digital Twin, Plan
      for the next short period
Result: Network configuration
initialization;
repeat
    Wait for the next event;
    updates the process images;
    calculates the operation mode for the next
     period;
    select the set of services/parameters to
     accomplish the goal;
    if *the next state is not allowed* **then**
        negotiate with HPUs capable of supplying
         the necessary services;
        evaluate the set of feasible configurations
         according to the service offerings by the
         HPU (use the Abstracted Hybrid Dynamics
         Models of the HPU);
        select the optimal configuration;
        build the Temporal HPU and its supervisor;
        send the cooperation rules to the selected
         HPU;
    end
until *for ever*;

SCADA systems are a well-established technology in industrial process control and are part of the proposed architecture solution. SCADA systems have an interface layer with the field, associated with instrumentation, a layer associated with the controllers, and a supervision and data acquisition layer that allow to maintain control of the processes on the plant floor. Additional sensors may be necessary to
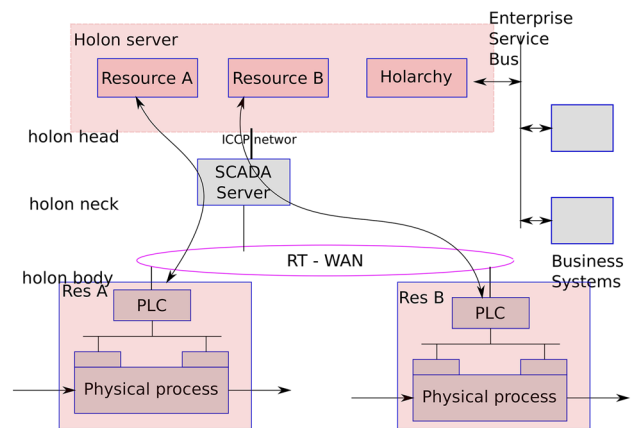

**Fig. 11** Holons into the IT/OT architecture for WSS

implement the holonic vision that allows to have the information of the resource, and of the execution of the order. In relation to the RAMI4.0 reference model, it can be indicated that the SCADA covers its levels L1, L2, L3 (Zezulka et al., 2016). For the case study, the sensors of the treatment plant allow to follow the evolution of the processes (execution of the order), and the start, stop events for the filters and settlers are received from the SCADA. In the extended real-time servers associated with SCADA, the evolution of the process and the status of the resources are monitored. These functions correspond to the bottom layers of Fig. 8.

IT for the upper layer of HPU

Each physical resource or group of physical resources that perform a stage or sub-stage of a production process considered as a resource holon, and it is composed of two elements (a) its image (b) the description (knowledge) in the holon server as shown in Fig. 12 and corresponds to the smart part of the Holon. SCADA information updates the image, and process experts create its knowledge. These components are stored in the extended real-time part of the SCADA system. Each unit has knowledge associated with the product model, capabilities and abilities from its process models, and physical connections between the different resources and PIM (which correspond to the EH).

The upper layer in Fig. 8 correspond to the planning, scheduling, and re-scheduling activities of the HPU. These functions are performed on-line according to the inputs and requirements flows for the plant, increasing availability into the systems. The SCADA transmits to the extended real-time servers the events captured on the plant floor or the SCADA's commands, updating the holon image. Process events update the status of the order and events associated with the resource that allows inferring the resource's status.

Fig. 12 UML deployment diagram of the HPU software components
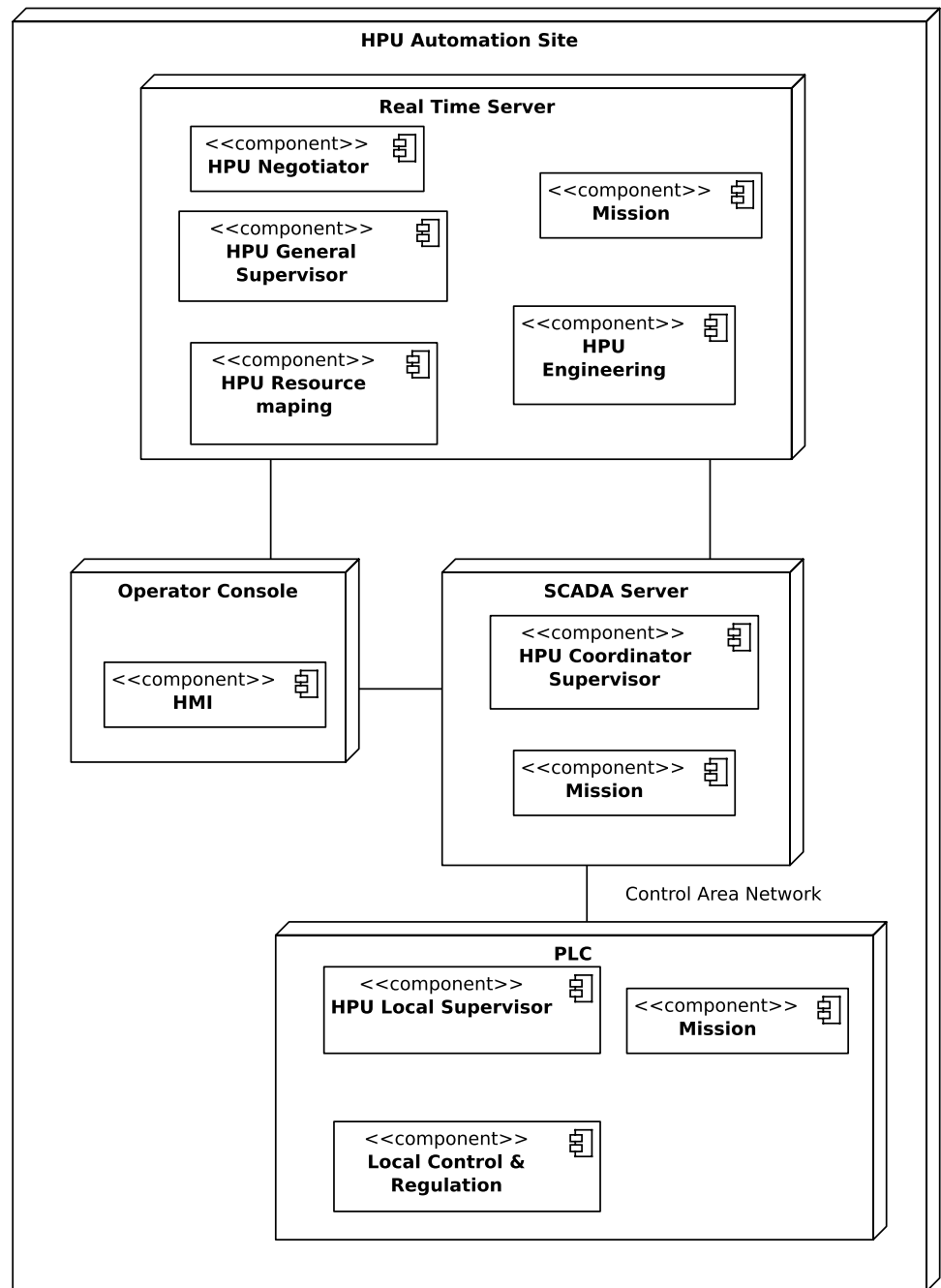
In Fig. 11 the mapping of the hierarchy levels of the HPU on the IT/OT architecture is given.

To implement supervisors, it is necessary to have engines that receive a supervision model and execute the supervision tasks defined for that model. In our case, the motor used is based on a meta-model described using Petri nets. At the lower level, OT events at the plant floor are detected directly by sensors and/or by detection mechanisms regarding the operation regions. Other plant events come from the equipment monitoring. Other plant events come from the

equipment monitoring. Supervisor receives these events to determine the following operation mode. External conditions are managed similarly. The occurrence of the events updates the abstractions (process and equipment images). All the events defined to describe the behavior of the physical system must have an associated sensor or a detection mechanism based on the measurements of the system. This allows to reconstruct the discrete dynamics, and to have an updated image that can be used to reprogram the system. According to the aim of this paper and is suggested by Liu

and Xie (2020) into the technology available are soft-sensors, which are usually used in the chemical and petrochemical industry, power generating industry, because they require a high precision level, is essential to consider this kind of sensors to monitor the process. Kernel-based soft sensors are a suitable option to recognize and indicate abnormal events or a faults. A general way is to compare actual values, typical situations of WSS.

The functions of optimization and production programming are deployed using infrastructure IT. Servers oriented to maintain the HPU information, maintain the updated image of the process through update mechanisms by events. Plant floor events of the OT, travel to the management level of the HPU and a motor updates the status. If the state does not correspond to the expected state, the reprogramming mechanisms are triggered.

The Product Models and Process Models are maintained on specialized servers, which can be updated by the engineering and development staff. The relationships between the resource holons, and the product holons are similar to those proposed by McFarlane and Bussmann (2003).

The head of the holon has the whole description of the resource and its process image. The image of the tasks that a resource is executing are compared with the prediction obtained from the behavior model corresponding to the task. The behavior model is used both for planning and to determine if the evolution is as expected. The functionality is similar to that described in Monostori et al. (2016). Details of the software components at the holon server are given in Fig. 12.

Linking process events and product events

The evolution of the discrete part of the dynamics of the process is driven by the appearance of events. A subset of these events are sent to the product evolution supervisor in order to change the system configuration if necessary. The appearance of events on the plant floor, captured by the controllers, allows the evolution of the process to be monitored. The list of all events, and the association with the events of the Product Model, allows the supervision of the stage. This event association map is part of the description of vertical integration.

For instance, events can be generated by external resources such as users using phone calls to inform about the water network conditions or external applications that make "data analytics" determine leaks or changes in the network. Those events travel on the computer network until the extended real-time servers and the evaluation cycle is started to process those events like the events detected internally.
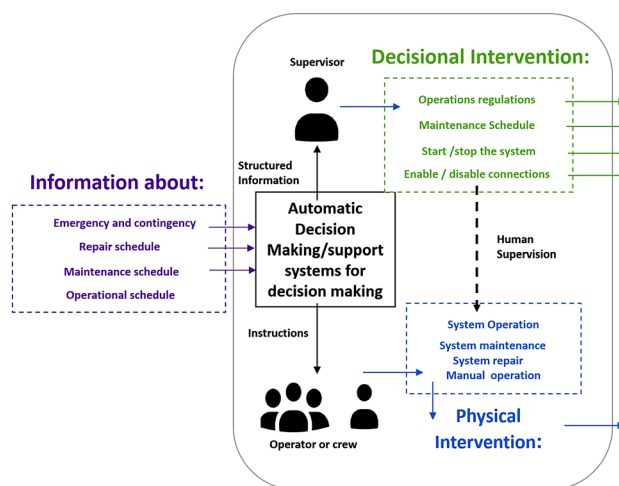

Fig. 13 Human in the loop

Generation of production objectives for the HPU

In Large Scale Processes (LSP) such as WSS, the integration between the regulatory control functions and the planing functions is a need. These two functions are split into a hierarchy (Risbeck et al., 2019). Scheduling and re-scheduling process determine what are the "optimal" configuration to accomplish the production objectives. The daily optimization of the system balances the volume of water at the entrance of the treatment plants, the capacity of the main network (pumps, pipe diameters, network topology), storage capacity in distribution tanks and hourly demand. of the secondary networks (see Figs. 4 and 5). With this, the filling sequence of the different tanks and pressure reference for the secondary networks are determined using the algorithm shown in Algorithm 2.

The human in the loop

The human performs different roles in a LSP, (a) physical tasks that cannot be replaced by machines such as infrastructure maintenance, (b) supervision tasks in decision-making processes where expertise is essential due to the incompleteness of the models and c) providing knowledge to the system. In the decision-making process, the human must have the possibility of interacting in fully automated environments, to systems with manual decision-making (Cardin, 2019). Despite the human intervention in the operational level has been restricted to reduce variability in operations, the worker operator is indispensable in some situations as systems' repair and maintenance Lee et al., (2020).

The main roles of the human in the system are:

1. *Supervision of the physical operation* in the different HPUs. The system must allow the visualization of the processes and generate enough information for the operator to validate the decisions suggested by the system. The system shows the different flows, the current balance and the values that the system will have in the next few hours. The state of the resources. Therefore, human as a supervisor is in charge of evaluating the performance of the system, as proposed in (Emmanouilidis et al., 2019).

2. *Interaction with the users of LSPs* In many cases, failures in the system such as pressure drops or absence of service, leaks in the circuits, are detected by users who communicate with the service centers, and these failures must be introduced into the system for reconfiguration or for carrying out of a maintenance. The first attention is made by a human being who reports to the system and acts similarly to the "magical human" concept, making decisions and interacting with the physical and cyber to solve problems (Trentesaux and Millot, 2016).

3. *Management of events and contingencies* The automated system must have the ability to detect most equipment failures, line leaks, and verification of goal compliance. Such an event will generate a new configuration that must be proposed by the system and validated by an operator. If there is no valid output it is up to the operator to build one. The system must allow the operator to establish procedures to achieve a new configuration.

4. *Validation of optimizations* The configurations found automatically, must be validated by the operator before being sent to the execution level in real time.

5. *Loading of system knowledge* Technical personnel are the creators of the models on which the system works. This knowledge is introduced, validated by the process engineers, by the maintenance personnel, they define the HPUs and their models of behavior. There is a strong dependence on the cyber part of human expertise. Similarly, the fit of the models found by data analytics must be validated by the expert, determining the parameters of the control system optimization processes (Fantini et al., 2016).

6. *Manual operations* Many operations must be carried out manually, especially in the case of corrective maintenance of LSPs. The operator interacts with the HPU to indicate the progress of the operation. In the control room, operators must have feedback on the progress of maintenance operations. Human acts as a local entity of the control system at the operational level and develops a cooperative relationship with the system because of the high level of complexity, as introduced by Pacaux-Lemoine et al., (2018).
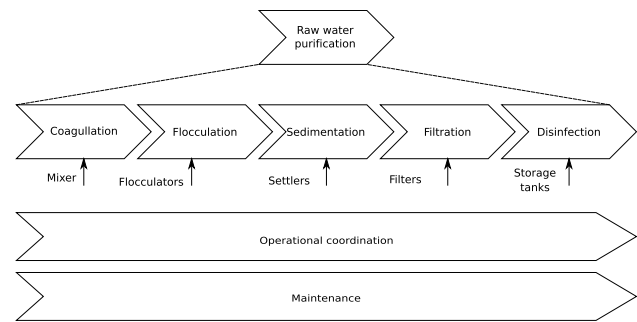

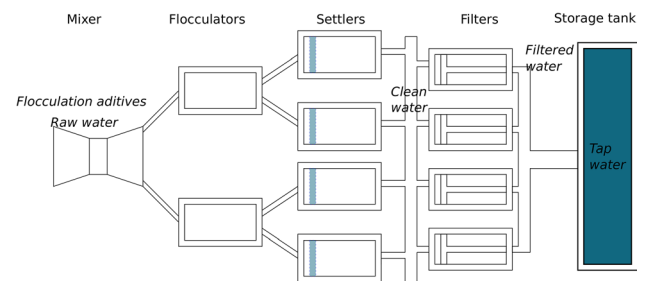**Fig. 14** Product Model for the purification process

Fig. 15 Product Model for the purification process

The information platform must allow easy human interaction with the system at all levels. The most complicated interaction mechanisms are associated with activities of maintenance, since the platform must ensure interaction between the operator and maintenance personnel, ensure the visibility of the equipment, show plans, equipment connections, etc. The Digital Twin is corresponding to equipment and processes and must be viewed by all personnel involved in the maintenance activity.

The Digital Twin allows representing the human as a is decisional human entity considering a water supply system the human role may be different depending on its location into the system as is shown in Fig. 13. As a supervisor it takes some decision as scheduled the maintenance, start or stop the system, decisions which are supported by structured information about the system. By the hand the human as an operator or a crew could have a reactive role, executing manual operations or maintenance activities. In this case, the human receives an instruction, and it intervenes in the system. Human participation in maintenance is required especially when the automatic system repair is enabled to solve failures.

Methodology to implement the HPU: application to a WSS

The proposed methodological approach shown here, it is structured based on HPU requirements and the preliminary requirements for I4.0 (See "WSS requirements established by Intelligent Manufacturing Systems for I4.0" section). It takes into account Product & Process Models that includes control and supervision laws, *PUs* hierarchies and interconnections among them (topology of the production network) and the IT/OT that support models, information exchange and decision systems.

Those steps are: (a) Supply the necessary knowledge to the system, (b) Decides the Hierarchy levels and Layers for the whole system (See "Literature review: intelligent automation systems addressing I4.0 requirements" section), taking into account the possible holarchies and the existing information systems, (c) make the mapping of the functional layers on the IT/OT infrastructure.

Knowledge acquisition

The source of knowledge is given by experts in the area who define the general models for water management in cities. These experts use different software applications to study water sources and their capabilities; characterize the demand associated with population growth. Using this knowledge, they design and build the infrastructure of the WSS.

The first step achieve an implementation is to obtain the Product Model and Process Models and the connectivity of the whole system. In the case of a WSS, the Product Model takes into account the principal stages that it can be found on the city water cycle given in 2. Those stages are shown in Fig. 2.

From the city water cycle of Fig. 2, it will be considered only the WSS. The model from sources until water consumption considers water input from the sources including
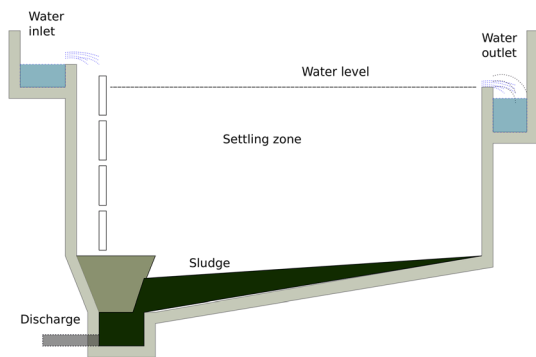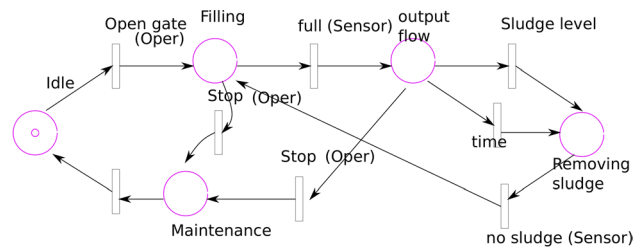

Fig. 17 Petri net of the behavior of the settler resource

rain and neighborhood water requirements fore-casting, and operation to estimate the optimal levels of reservoirs and the final pressure at the neighborhoods to assure the permanent water supply as was given by Fig. 3 that shows the historical behavior of rains and water consumption.

Sources Determination of the characteristics and behavior of the sources. Surface and underground. Reservoirs. Rain forecasting.

Water intake System to intake the underground or surface water and make it available to transport to the purification plants. Reservoirs. Determination of the raw water quality.

Transport of raw water Description of the transport system from reservoirs to purification plants.

Purification system This stage transform raw water in drinking water.

Distribution The pipeline network that transports drinking water from purification plants to distribution tanks.

Final distribution The secondary network that transports water for distribution tanks to final users. Behavior of neighborhoods.
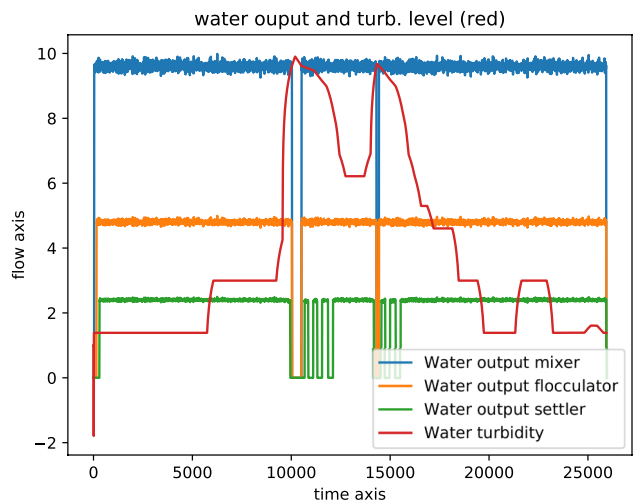

Fig. 16 Plan of a settler resource for the sedimentation substage

Fig. 18 Behavior of the flow in Mixer, Flocculator 1, settler for the turbidity level of the input water
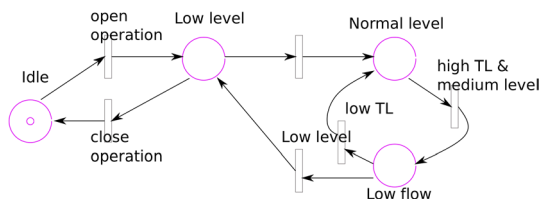
Fig. 19 Global behavior of a Purification plant process

Information on minimum acceptable water quality to users (Color, flavor, amount of bacteria, cleanliness, pressure, etc.), to pass from one stage to another.

Purification stage is in charge of taking raw water (from sources or reservoirs) and converting it into drinking water suitable for human consumption. This process is divided into several sub-stages as is shown Fig. 14, the firsts sub-stages (Coagulation, flocculation, sedimentation, filtration and disinfection) eliminates the turbidity of the raw water coming from the source, produced by very small diameter particles and low sedimentation (colloidal), which is achieved by adding a coagulant in the sedimentation-filtration process, and in the last one, microorganisms, that can be harmful to humans are eliminated, which is achieved by disinfection (chemical means: addition of chlorine). The last step also stores the product to buffer changes in demand and in the steps in the sedimentation and filtering sub-stages.

A purification plant is given in Fig. 15 and it corresponds to the case studied in (La Cruz, 2019), and it allows us demonstrate the methodology.

Product & process models

The construction of the models is focused on the resource. The product model reflects the chaining of resources, while the process model represents the resource's behavior when it performs an activity. Each resource has an internal behavior and an external behavior that results from the supervisor -system components used to coordinate and schedule production.

Product and Process Models are described formally Using Petri nets. The product model is associated to the stage (sub-stage) sequences for the product and the process model is associated to the steps inside the equipment that performs a stage or a sub-stage.

Taking as example the sedimentation sub-stage, a description of the process follows. In sedimentation, here the flocs that are in suspension are deposited; the rate of fall will depend on the concentration of the particles, the speed gradient of the system and the size distribution. The mass of water should remain between two and four hours

to decantation. At the top of the sedimentation tank there are collecting channels throughout the tank, linked by rows of perforated ducts that collect water in the clarified area. At the bottom of the sedimentation tank there is an inclination to a drain point, for easy removal of the flocs, opening a gate or valve. The settlers can be vertical, horizontal, laminar flow, their structure and configuration depend on the flow and quality of water. See Fig. 16.

For the plant, there are two settler for each flocculator, and the filters are common to the settlers. The Petri net for sedimentation process is given in Fig. 17, and in Fig. 18 the behavior of the settler.

Deploying the Holon over the IT/OT technology.

The bottom layers of the HPU and the OT

The set of possible configurations results from the combination of the Product Model with the collection of resources that provide the services specified in the Product Model.

$$Conf = PM \times Res_{available}$$

where $Res_{available} \subseteq Res$

The information about Res_i is obtained in PIM and the Digital Twin of Res_i. In this case possible configurations are:

$$\left(C - Fl_1 - S_1 - Fi_1 - D\right),$$

$$\left(C - Fl_1 - S_2 - Fi_1 - D\right),$$

$$(C - Fl_1 - \{S_1 || S_2\} - Fi_1 - D),$$

$$(C - \{Fl_1 - \{S_1 || S_2\} || Fl_2 - \{S_3 || S_4\}\} - \{Fi_1 || Fi_2 || Fi_3 || Fi_4\} - D)$$

The operation supervisor for the purification process coordinate the supervisors of sedimentation and filtering sub-stages, estimates the amount of drinking water output taking into account the quality of the raw water at the input (turbidity level), and the state of settlers and filters. The behavior of the HPU evolves according the quality of the raw water. The quantity of the raw water is determined by the water available at the reservoirs.

The global behavior of the Purification plant process is given in Fig. 19. The purification plant is a resource of the WSS system. Purification Plant has it own SCADA system, and is a smart resource for de WSS. Events that change the state of the purification plant are sent to the WSS SCADA where the same procedures are used to monitoring the global system.

Table 3 Comparison of classical vs. holonic WSS architectures addressing by the I4.0 requirements (see "WSS requirements established by Intelligent Manufacturing Systems for I4.0" section)

I4.0 Req	Classical WSS approach	Holonic WSS approach
CPPS	+	+ +
Indepen. (Req1.i)	Limited information available for MES functions. The robustness of the system is not guar-anteed (Sapkota et al. 2014)	HPU approach by the RH, SH, EH, and MH allows the interoperabil-ity of multiple open platforms. See "The technological architecture: HPU's IT/OT" section
IIoT(Req1.ii)	Poor IT integration by the cloud	HPU is able to get better IT integration with customer information, GIS, maintenance. See Holonic Production Unit architecture Section and Fig. 11
ISA-95(Req1.iii)	Typical shop floor regulation by simple control.Poor MES and ERP systems interactions	Decentralized regulatory control, event and fault detection from shop-floor until ERP systems by the RH. See Fig. 12
Smt. prod (Req1.iv)	Usually water has been not considered as a product, more as a service	Smart WSS integrate set of products, solutions, and systems. HPU con-siders the Product Model as a part of EH. See "Modeling the behavior of the global system" section
Smartness	–	+ +
Autonomy (Req2.i)	Poor autonomy. Traditional centralized services (Sapkota et al. 2014)	HPU architecture considers each resource as autonomous—cooperat-ing. The control and supervision mechanisms are mapped on elements
of the IT/OT architecture available. See Subsection 4.2		
Open net. (Req2.ii)	Supervision by operators using visualization of process variables and real-time applications	HPU is based on the existence of sensors and actuators at plant level
Coopera. (Req2.iii)	Poor cooperation among systems. Different utilities/depart-ments often manage various components of urban water and resources sep-	
arately (Sapkota et al. 2014)	Three dynamic models describe the HPU process's evolu-tion: process,product, order, and structural models for resources. A product based on goal "stages" and the dynamics and capacities of internal resources determine HPU capacity and availability. See "Holonic Production Unit architecture" Section	
Proact. (Req2.iv)	By operator expertise. Developments based on the hydrau-lic model to detect inconsistencies. Low data analytic to detect failures	In case of failures of an HPU, a new configuration is recommended
to the operators including the operation sequence. Also the smart tracking from the HPU provides feedback to the operator to report anomalies. See "Supervisor Holon (SH)" section		
Models	+	+ +
Modelling (Req3.i)	Typically, high standards process to make water drinkable (quality of the product)	HPU corresponds to the Hierarchy and Layers axes of the RAMI4.0 (DIN SPEC 91,345 norm) for the processes quality and performance
Abstract. (Req3.ii)	The structure and dynamics of the network are based on the hydraulic model	HPU uses Hydraulic Model plus Hybrid systems to describe the be-havior of the WSS and also for the assets hierarchy, which allowplan-ning, programming and monitoring of operations ("Holonic Production Unit architecture" Section)

Table 3 (continued)

I4.0 Req	Classical WSS approach	Holonic WSS approach
IDE		
(Req3.iii)	SCADA / Extended RT-servers	SCADA / Extended RT-servers
	+	+
Human		
Domain (Req4.i)	Broad range of non-conventional WSS technolo-gies such as rainwater tanks, stormwater harvesting, and wastewater reuse within the sys-tem (Sapkota et al. 2014)	Smart WSS should comprise smart meters, smart valves, smart
	pumps (Li et al. 2020), and work with soft-sensors (Liu and Xie, 2020). The RH integrates multiples resource domains as unified service units rather than individual components. See Sect. 5	
Hybrid (Req4.ii)	Hybridization process where the mix of centralized and decentralized systems co-exists is possible (Sapkota et al. 2014)	HPU can consult the OT components (from several brands) to hybrid
	topologies implementation with open communication protocols, e.g., using OPC UA to give updated infor-mation to the operator and upper systems. See Fig. 9.b	
Hum.fact. (Req4.iii)	Sunk investments and a well-established socio-technical regime creates the path dependencies that flavor the prevalence of centralized models	Smart WSS provides many ways technology, middleware, and soft-
	ware help maximize the value of smart Metering data to all stake-holders. The integration using the Enterprise Bus Service and the extended RT environment is used by the HPU architecture in Fig. 11	
RAMI4.0		
Hierarchy (Req5.i)	–	+
	A fully hierarchical water servicing system frequently only focuses on provides clean drinking water, sanitation, and protection from urban flooding (cost-effective and reli-able) (Sapkota et al. 2014)	Product Models are specified by the services provided by the HPU, together with IT, and its implementation of control and supervision mechanisms are adapted to the classical OT (L0-L4). An image main-tains all information on what is happening at shop floor and follows the events' process dynamics (DT concept). See "Modeling the behavior of the global system" and "Supervisor Holon (SH)" sections
Layers (Req5.ii)	No multiple service layers (only for final users	
	and WSS management). WSS is considered to be unsuit-able to address future challenges, i.e., unsustainable services (Sapkota et al. 2014)	The main activities of the RAMI4.0 layers cover by the resource layers of the HPU, as shown Fig. 20
Life-cycle (Req5.iii)	There are two main subsystems within the urban water cycle: the rainfall-stormwater discharge and supply-waste-water system (Sapkota et al. 2014)	HPU proposes the concept of intelligent RH as a central element and describes the product life-cycle in terms of services provided to fulfill the mission. The link between different HPUs give the horizontal axis corresponding to the value chain. This route is determined according to an optimization criterion. See "The technological architecture: HPU's IT/OT" section

Evaluation and discussion of the HPU architecture

This section briefly evaluates and discusses how the characteristics of the currently installed automation and integration of the proposed HPU architecture meet the I4.0 requirements expressed in "WSS requirements established by Intelligent Manufacturing Systems for I4.0" section.

The IT-intensive WSS platforms have been named *Smart Water Management* (Li et al., 2020). They differ from traditional water management technologies by including regulation, scheduling using real information from the WSS similar to the CPPS requirements. Establishing a criterion to measure HPU regarding the compliance of an intelligent WSS is difficult since there are no standardized CPPS metrics (Nikolakis et al., 2020). Therefore, for completeness reasons, a set of criteria has been adopted using the requirements of I4.0 (see "WSS requirements established by Intelligent Manufacturing Systems for I4.0" section), and Table 3 discusses its achievement of the classical architecture versus holonic WSS.

Advanced and intelligent WSS includes IT integration (Li et al., 2020), that is, intelligent water networks, like any data ecosystem, are hierarchical. It goes from sensors (L0), remote control and communication (L1), continues to data acquisition, supervision and visualization systems (L2), operations management, data analytics (L3) to the business management level (L4). An intelligent WSS architecture can be characterized by five layers: physical layer, detection and control layer, communication layer, data management layer, and data fusion layer. The WSS is a network of connected resources that works in different configurations to guarantee service to the population and must be resilient to changes in demand, failures, etc. (Rahmani et al., 2018).

Discussion: main activities from the HPU

An HPU, to maintain its autonomy, must possess the necessary knowledge to make decisions. This knowledge is given by the model of the physical behavior of the plant. The other elements necessary for decision making are: the state of the system, and the objective to be achieved, see Fig. 20. The knowledge of the HPU is provided at the beginning by the specialists, and it is adjusted based on the information collected from the different executions of the operation. The algorithms for calculating the outputs are part of the knowledge provided initially.

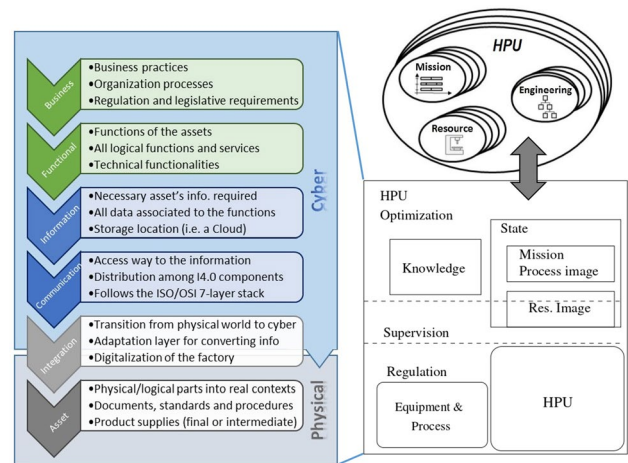The inputs to the decision-making system are:

Fig. 20 RAMI4.0 Layers' main activities from the HPU

1. Measurements generated in the physical systems, which may be stored or have already been processed. The current condition of the system results from process measurements that are transformed into the state of the HPU.
2. Production targets, which can be supplied by humans, or results from another HPU. This information will be used to determine the internal objectives to be met by the unit, the definition of procedures, the parameterization of controllers, etc.
3. The rules of cooperation, which can be considered as knowledge, that specify the forms of interaction between different HPUs, and the possible connections between them.

The outputs are of two types: first, the Internal objectives that are parameters to its resources, procedures. Second, the Information about the status of the HPU, events that alter its behavior and that must be handled by other HPUs. To obtain the condition of the units, it is necessary, at least to have, with the operating condition of the inflow (obtained from the inflow model), the operating condition of the unit (it is obtained from the operative condition of the resources (equipment and infrastructure given from maintenance), the operational condition of the supplies (given by reservoirs) and the operational knowledge of the human resource.

Benefits and limitations of the HPU architecture about the existent WSS

Compared to the WSS currently in operation, the expected changes are summarized as follows:

Benefits. (1) The evaluation of the possible configurations of the systems will be carried out automatically. (2) the SH will generate the sequences of operations for the

configuration changes. (3) Improvements in predictions of WSS behavior for different operating conditions.

Limitations (1) Difficulties in the construction and validation of behavior models for each functional unit that are compatible with each other. (2) Complexity in the integration with the hydraulic model for WSS's global monitoring of operations.

Conclusion

Following the preliminary design in (Cruz S. et al., 2019), an HMS architecture is expanded for continuous processes into WSS. The HMS is based on the concept of HPU that contains three fundamental holons: RH, MH, and EH. An additional holon, called SH, similar to the ADACOR's evolution proposed by Barbosa et al., (2015), allows the supervision and control tasks for each HPU. Under this premise, HPUs can react to an unexpected disturbance. The mechanisms of high-level cooperation, as well as the establishment of global objectives, are achieved by elements that model the physical behavior of the processes and allow maintaining a coherent operation between units. This idea is similar to that of a Digital Twin concept. HPU involves the Human in the loop concept to get specific roles -e.g., decision-making features, probably defined by humans (or supervised by humans).

In summary, a cooperation between units is achieved by establishing viable global configurations and selecting the optimal one. The formation of individual behavior models allows us to determine global behaviors through simulation. Each HPU is modeled separately, and the composition of models establishes configurations modes. These configurations ensure a stable and continuous operational state, even if the outcome is not perfectly accomplished. The article shows how the HPU architecture can meet the requirements of I4.0, limited by the Hierarchy Levels and the Layers (two RAMI4.0 axes).

References

Barbosa, J., Leitão, P., Adam, E., & Trentesaux, D. (2015). Dynamic self-organization in holonic multi-agent manufacturing systems: The ADACOR evolution. *Computers in Industry, 66*, 99–111. https://doi.org/10.1016/j.compind.2014.10.01

Blanc, P., Demongodin, I., & Castagna, P. (2008). A holonic approach for manufacturing execution system design: An industrial application. *Engineering Applica-Tions of Artificial Intelligence, 21*(3), 315–330. https://doi.org/10.1016/j.engappai.2008.01.007

Bloch, H., Fay, A., Knohl, T., Hensel, S., Hahn, A., Urbas, L., Wassilew, S., Bernshausen, J., Hoernicke, M., Haller, A., (2017) Model-based engineering of cpps in the process industries. In: 2017 IEEE 15th International Conference on Industrial Informatics (INDIN), IEEE, pp 1153–1159, DOI https://doi.org/10.1109/INDIN.2017.8104936

Borangiu, T., Raileanu, S., Trentesaux, D., Berger, T., & Iacob, I. (2014). Distributed manufacturing control with extended cnp interaction of intelligent products. *Journal of Intelligent Manufacturing, 25*(5), 1065–1075. https://doi.org/10.1007/s10845-013-0740-3

Borangiu, T., Trentesaux, D., Thomas, A., Cavalieri, S., (eds) (2019) Service Orientation in Holonic and Multi-Agent Manufacturing, vol 803 Springer. DOI https://doi.org/10.1007/978-3-030-03003-2

Brdys, M., & Roberts, D. (1986). Optimal structures for steady- state adaptive optimizing control of large-scale industrial processes. *International Journal of Systems Science, 17*(10), 1449–1474. https://doi.org/10.1080/00207728608926900

Candelieri, A., & Archetti, F. (2014). Identifying typical urban water demand patterns for a reliable short-term forecasting – the ice-water project approach. *Procedia Engineering, 89*, 1004–1012. https://doi.org/10.1016/j.proeng.2014.11.218,16thWaterDistributionSystemAnalysisConference,WDSA2014

Cardin, O. (2019). Classification of cyber-physical production systems applications: Propositionofan analysis framework. *Computers in Industry*. https://doi.org/10.1016/j.compind.2018.10.002

Chacón, E., Besembel, I., Rivero, D., & Cardillo, J. (2009). Embedded holonics systems in production process: Holonic unit of production. Revista T´ecnica de la Facultad de Ingenier´ıa Universidad del Zulia 32(1)

Chokshi, N., & McFarlane, D. (2008a). A distributed architecture for reconfigurable control of continuous process operations. *Journal of Intelligent Manufacturing, 19*(2), 215–232. https://doi.org/10.1007/s10845-008-0075-7

Chokshi, N. N., & McFarlane, D. C. (2008b). A distributed coordination approach to reconfigurable process control. *Springer*. https://doi.org/10.1007/978-1-84800-060-5

Colombo, A., Schoop, R., & Neubert, R. (2006). An agent-based intelligent control platform for industrial holonic manufacturing systems. *IEEE Transactions on Industrial Electronics, 53*(1), 322–337. https://doi.org/10.1109/TIE.2005.862210

Colombo, A. W., Gepp, M., Barata, J., Leitão, P., Barbosa, J., Wermann., J., (eds) (2019). Digitalized and harmonized industrial production systems, 1st edn. CRC Press, First edition.—Boca Raton, FL: CRC Press/Taylor & Francis, 2019. https://doi.org/10.1201/9780429263316, https://www.taylorfrancis.com/books/9780429553899

Cruz S., L. A., & Vogel-Heuser, B., (2017). Comparison of agent oriented software methodologies to apply in cyber physical production systems. In: 2017 IEEE 15th International Conference on

Industrial Informatics (INDIN), IEEE, pp 65–71. https://doi.org/10.1109/INDIN.2017.8104748

Cruz S., L. A., Rojas, A. O. A., Chacón, E., (2019) Service Orientation in Holonic and Multi-Agent Manufacturing, Springer International Publishing, chap Implementing Industrial Control Automation for Holonic Manufacturing Systems based on the Production Unit Architecture, pp 1–14. DOI https://doi.org/10.1007/978-3-030-03003-2_18

Derigent, W., Cardin, O., & Trentesaux, D. (2020). Industry 4.0: contributions of holonic manufacturing control architectures and future challenges. *Journal of Intelligent Manufacturing*. https://doi.org/10.1007/s10845-020-01532-x

Dias-Ferreira, J., Ribeiro, L., Akillioglu, H., Neves, P., & Onori, M. (2018). Biosoarm: a bio-inspired self-organising architecture for manufacturing cyber-physical shopfloors. *Journal of Intelligent Manufacturing*. https://doi.org/10.1007/s10845-016-1258-2

Emmanouilidis, C., Pistofidis, P., Bertoncelj, L., Katsouros, V., Fournaris, A., Koulamas, C., & Ruiz-Carcel, C. (2019). Enabling the human in the loop: Linked data and knowledge in industrial cyber-physical systems. *Annual Reviews in Control, 47*, 249–265. https://doi.org/10.1016/j.arcontrol.2019.03.004

Fantini, P., Tavola, G., Taisch, M., Barbosa, J., Leitao, P., Liu, Y., Sayed, M. S., Lohse, N., (2016) Exploring the integration of the human as a flexibility factor in cps enabled manufacturing environments: Methodology and results. In: IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society, pp 5711–5716. https://doi.org/10.1109/IECON.2016.7793579

Galán, R., Jiménez, A., Sanz, R., Mat´ıa, F., (2000) Control inteligente. Inteligencia Artificial Revista Iberoamericana de Inteligencia Artificial. 4(10). https://doi.org/10.4114/ia.v4i10.661

Gamboa, Q. F., Kubler, S., Cardin, O., & Castagna, P. (2013). Product specification in a service-oriented holonic manufacturing system using petrinets. *Intelligent Manufacturing Systems*. https://doi.org/10.3182/20130522-3-BR-4036.00094

Gamboa, Q. F., Cardin, O., LAnton, A., Castagna, P., (2015) Process specification framework in a service oriented holonic manufacturing systems. In: T. Borangiu, A. Thomas, D. Trentesaux (eds) Service Orientation in Holonic and Multi-agent Manufacturing, Springer, pp 81–89. https://doi.org/10.1007/978-3-319-15159-5 8

García, V. M., López, I. R., & Villar, L. F. (2013). iland: An enhanced middleware for real-time reconfiguration of service oriented distributed real-time systems. *IEEE Transactions on Industrial Informatics, 9*(1), 228–236. https://doi.org/10.1109/TII.2012.2198662

Giret, A., & Botti, V. (2009). Engineering holonic manufacturing systems. *Computers in Industry, 60*(6), 428–440. https://doi.org/10.1016/j.compind.2009.02.007

Harjunkoski, I., Nyström, & R., Horch, A. (2009). Integration of scheduling and control—theory or practice? *Computers & Chemical Engineering*, *33*(12), 1909–1918. https://doi.org/10.1016/j.compchemeng.2009.06.016

Hsieh, F. S. (2009). Collaborative reconfiguration mechanism for holonic manufacturing systems. *Automatica, 45*, 2563–2569.

Indriago, C., Cardin, O., Rakoto, N., Castagna, P., Chacon, E., (2014) Application du paradigme holonique a un systéme de reservoirs. In: MOSIM 2014, 10ème conférence Francophone de Modelisation, Optimisation et Simulation.

Jiménez, F., Bekrar, A., Zambrano-Rey, G., Trentesaux, D., & Leitão, P. (2017). Pollux: A dynamic hybrid control architecture for flexible job shop systems. *International Journal of Production Research, 55*(15), 4229–4247. https://doi.org/10.1080/00207543.2016.1218087

Joannou, D., Kalawsky, R., Saravi, S., Rivas Casado, M., Fu, G., & Meng, F. (2019). A model-based engineering methodology and architecture for resilience in systems-of-systems: A case of water supply resilience to flooding. *Water, 11*(3), 496. https://doi.org/10.3390/w11030496

Karnouskos, S., Colombo, A.W., Bangemann, T., Manninen, K., Camp, R., Tilly, M., Stluka, P., Jammes, F., Delsing, J., Eliasson, J. (2012) A soa-based architecture for empowering future collaborative cloud-based industrial automation. In: IECON 2012–38th Annual Conference on IEEE Industrial Electronics Society, IEEE, pp 5766–5772. DOI https://doi.org/10.1109/IECON.2012.6389042

La Cruz, Y., (2019) Propuesta de gemelo digital para el proceso de potabilización en hidrologicas desde la visión de la industria 4.0,. Trabajo de grado, Escuela de Ingeniería de Sistemas. Facultad de Ingeniería. de Universidad de Los Andes.

Lee, J., Ni, J., Singh, J., Jiang, B., Azamfar, M., & Feng, J. (2020). Intelligent maintenance systems and predictive manufacturing. *Journal of Manufacturing Science and Engineering, 11*, 1–40. https://doi.org/10.1115/1.4047856

Leitão, P., & Restivo, F. J. (2008). Implementation of a holonic control system in a flexible manufacturing system. *IEEE Transactions on Systems Man and Cybernetics Part C Applications and Reviews., 38*(5), 699–709. https://doi.org/10.1109/TSMCC.2008.923881

Leitão, P., Karnouskos, S., Ribeiro, L., Lee, J., Strasser, T., Colombo, A. W., (2016) Smart agents in industrial cyber– physical systems. Proceedings of the IEEE 104(5):1086– 1101. https://doi.org/10.1109/JPROC.2016.2521931

Lennartson, B., Bengtsson, K., Wigström, O., & Riazi, S. (2016). Modeling and optimization of hybrid systems for the tweeting factory. *IEEE Transactions on Automation Science and Engineering, 13*(1), 191–205. https://doi.org/10.1109/TASE.2015.2480010

Li, J., Yang, X., & Sitzenfrei, R. (2020). Rethinking the framework of smart water system: A review. *Water, 12*(2), 412. https://doi.org/10.3390/w12020412

Liu, Y., & Xie, M. (2020). Rebooting data-driven soft-sensors in process industries: A review of kernel methods. *Journal of Process Control, 89*, 58–73. https://doi.org/10.1016/j.jprocont.2020.03.012

Lygeros, J., Sastry, S., & Tomlin, C. (2012). *Hybrid Systems: Foundations, advanced topics and applications*. Verlag: Springer.

Marsalek, J., Jiménez-Cisneros, B., Malmquist, P. A., Karamouz, M., Goldenfum, J., Chocat, B., (2006) Urban water cycle processes and interactions. International Hydrological Programme (IHP) UNESCO

McFarlane, D. C., Bussmann, S., (2003) Holonic manufacturing control: Rationales, developments and open issues. In: Agent-based manufacturing, Springer, pp 303–326, DOI https://doi.org/10.1007/978-3-662-05624-0 13

Mesarovic, M., Macko, D., & Takahara, Y. (1970). Two coordination principles and their application in large scale systems control. *Automatica, 6*(2), 261–270. https://doi.org/10.1016/0005-1098(70)90097-X

Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sihn, W., & Ueda, K. (2016). Cyber-physical systems in manufacturing. *CIRP Annals, 65*(2), 621–641. https://doi.org/10.1016/j.cirp.2016.06.005

Morari, M., Baotic, M., & Borrelli, F. (2003). Hybrid systems modeling and control. *European Journal of Control, 9*(2–3), 177–189.

Nam, T., Pardo, T. A., (2011) Conceptualizing smart city with dimensions of technology, people, and institutions. In: Proceedings of the 12th annual international digital government research conference: digital government innovation in challenging times, ACM, pp 282–291. https://doi.org/10.1145/2037556.2037602

Nikolakis, N., Senington, R., Sipsas, K., Syberfeldt, A., & Makris, S. (2020). On a containerized approach for the dynamic planning and control of a cyberphysical production system. *Robotics and Computer-Integrated Manufacturing, 64*, 101919. https://doi.org/10.1016/j.rcim.2019.101919

Pacaux-Lemoine, M., Berdal, Q., Enjalbert, S., Trentesaux, D., (2018) Towards human-based industrial cyber-physical systems. In: 2018

IEEE Industrial Cyber-Physical Systems (ICPS), pp 615–620, DOI https://doi.org/10.1109/ICPHYS.2018.839077

Pacaux-Lemoine, M., Berdal, Q., Enjalbert, S., Trentesaux, D., (2018) Towards human-based industrial cyber-physical systems. In: 2018 IEEE Industrial Cyber-Physical Systems (ICPS), pp 615–620, DOI https://doi.org/10.1109/ICPHYS.2018.8390776

Pérez, F., Irisarri, E., Orive, D., Marcos, M., Estevez, E., (2015) A cpps architecture approach for industry 4.0. In: Emerging Technologies & Factory Automation (ETFA), 2015 IEEE 20th Conference on, IEEE, pp 1–4. https://doi.org/10.1109/ETFA.2015.7301606

Plattform Industrie 4. 0 (2018) The structure of the administration shell: Trilateral perspective from france, italy and germany. Tech. rep., Plattform Industrie 4.0, URL https://www.plattform-i40.de/I40/Redaktion/EN/ Downloads/Publikation/hm-2018-trilaterale-coop.pdf? blob=publicationFile&v=5

Platzer, A. (2010). Logical analysis of hybrid systems: Proving theorems for complex dynamics. *Springer*. https://doi.org/10.1007/978-3-642-14509-4

Pujo, P., Broissin, N., & Ounnar, F. (2009). Prosis: An isoarchic structure for hms control. *Engineering Applications of Artificial Intelligence, 22*(7), 1034–1045.

Rahmani, F., Muhammed, K., Behzadian, K., & Farmani, R. (2018). Optimal operation of water distribution systems using a graph theory–based configuration of district metered areas. *Journal of Water Resources Planning and Management, 144*(8), 04018042. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000941

Ribeiro, L., & Hochwallner, M. (2018). On the design complexity of cyberphysical production systems. *Complexity*. https://doi.org/10.1155/2018/4632195

Risbeck, M. J., Maravelias, C. T., & Rawlings, J. B. (2019). Unification of closed-loop scheduling and control: State-space formulations, terminal constraints, and nominal theoretical properties. *Computers & Chemical Engineering, 129*, 106496. https://doi.org/10.1016/j.compchemeng.2019.06.021

Salvador Palau, A., Dhada, M. H., & Parlikad, A. K. (2019). Multi-agent system architectures for collaborative prognostics. *Journal of Intelligent Manufacturing, 30*(8), 2999–3013. https://doi.org/10.1007/s10845-019-01478-9

Sapkota, M., Arora, M., Malano, H., Moglia, M., Sharma, A., George, B., & Pamminger, F. (2014). An overview of hybrid water supply systems in the context of urban water management: Challenges and opportunities. *Water, 7*(12), 153–174. https://doi.org/10.3390/w7010153

Seitz, M., Gehlhoff, F., Cruz S., L. A. Fay, A., & Vogel-Heuser, B. (2021). Automation platform independent multi-agent system for robust networks of production resources in industry. *Journal of Intelligent Manufacturing.* https://doi.org/10.1007/s10845-021-01759-2

Tazaki, Y., Imura, Ji (2008) Bisimilar finite abstractions of interconnected systems. In: International Workshop on Hybrid Systems: Computation and Control, Springer, pp 514–527, DOI https://doi.org/10.1007/978-3-540-78929-1 37

Todini, E., Pilati, S., (1988) Computer applications in water supply, research study Press, chap a gradient method for the analysis of pipe networks, pp 1–20

Trentesaux, D. (2009). Distributed control of production systems. *Engineering Applications of Artificial Intelligence, 22*(7), 971–978. https://doi.org/10.1016/j.engappai.2009.05.001

Trentesaux, D., Millot, P., (2016). A human centred design to break the myth of the magic human in intelligent manufacturing systems. In: T. Borangiu, D. Trentesaux, A. Thomas, D. McFarlane (eds) Service orientation in holonic and multi-agent manufacturing vol 640. Springer, Cham. https://doi.org/10.1007/978-3-319-30337-6 10

Valckenaers, P. (2020). Perspective on holonic manufacturing systems: Prosa becomes arti. *Computers in Industry, 120*, 103226. https://doi.org/10.1016/j.compind.2020.103226

Vogel-Heuser ,B., Diedrich, C., Pantförder, D., Göhner, P., (2014) Coupling heterogeneous production systems by a multiagent based cyber-physical production system. In: Industrial Informatics (INDIN), 2014 12th IEEE International Conference on, IEEE, pp 713–719, DOI https://doi.org/10.1109/INDIN.2014.6945601

Zapata, G., (2011) Propuesta para la planificación, programación, supervisión y control de la producción en procesos continuos desde la teoría del control supervisorio y el enfoque holónico. PhD thesis, Facultad de Ingeniería. Universidad de Los Andes, Mérida, Venezuela

Zezulka, F., Marcon, P., Vesely, I., Sajdl, O., (2016) Industry 4.0–anintroduction in the phenomenon. IFAC-PapersOnLine 49(25):8–12, DOI https://doi.org/10.1016/j.ifacol.2016.12.002, 14th IFAC Conference on Programmable Devices and Embedded Systems PDES 2016