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MODELLING AND MULTI-AGENT IMPLEMENTING FRAMEWORK OF SERVICE-ORIENTED, HOLONIC ENVIRONMENT CONTROL SYSTEMS

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This article introduces a modelling framework for interconnected environment control processes represented as services (EServices), based on generic specifications that allow the customized design and configuration of environment control architectures for multi-room production plants of radioactive materials. The relational EService model is sub-ordinated to the concept of holonic control; three basic types of holons interact in a holarchy derived from the PROSA reference architecture, under the supervision of an expertise holon that has a global image of the plant rooms' environment conditions, requirements and control interdependencies. The representation, assessment, configuring and implementation of EServices with specific data structures models in different perspectives their type, features, functionalities, interdependencies and usage: (i) the EService Type perspective identifies a requested type of service included in an existing service-ontology; (ii) the EService Specification perspective allows the client (the environment conditioning application) to define the plant's environment needs; (iii) the EService Profile perspective is used by resources to publish their capabilities matching the needed EService Type, and to expose them in (iv) the EService Configuring and Implementation perspective. Transposing the theory of services in the holonic paradigm to environment conditioning processes leads to the Service-oriented Holonic Environment Control System (SoHECS) implemented in multi-agent framework. A case study exemplifies SoHECS design for a radiopharmaceuticals production line, experimental results being reported for cleanness control.

Keywords: Environment Control, EService, SOA, Holonic paradigm, Multi-agent system, Radiopharmaceuticals production

1. Introduction

Control theory in environment conditioning tasks is traditionally concerned with the design of static algorithms and control laws for a group of parameter-related (temperature, pressure and relative humidity) nonlinear processes, represented by fixed control modes and sequences with invariant timing and sample periods for sensory data acquisition and command update. The fixed

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control laws and sequences are off-line defined considering a priori known models of closed workspaces and HVAC processes (Heat and Ventilation Automatic Control), and the stability and precision set point tracking requirements. In this case, the environment parameters are regulated continuously in individual and isolated closed spaces [1, 2].

However, in the case of environment parameter control for multiple interrelated workspaces, like those com-posing a production facility or multistage plant (e.g., a radiopharmaceutical production facility), it is needed to provide flexibility to configure process control; this means both the capability to change in real time room parameter ranges, control laws and timings in order to satisfy a global facility environment model (e.g., cascaded pressures), and to switch between control modes and assigned resources (e.g., HVAC channels) in response to external predicted events (e.g., seasonal conditions) or unexpected events (e.g. resource breakdowns) [3, 4].

The holonic approach provides the above-mentioned attributes of flexibility, agility and optimality based on completely decentralized control architectures composed by social organizations of intelligent entities (the holons). For reality awareness and robustness of production systems, semi-heterarchical holonic models of process and activity control were developed to offer a dual behaviour that maintains at centralized level the global plant model, while reconfiguring at disturbances set points or control modes of local process controllers on the decentralized level. The informational part of holons is implemented by autonomous and collaborative entities - the agents. The dual topology can be applied to distributed monitoring and control of plant environment parameters.

The design of a HECS is performed in three successive steps: 1) Defining the *holarchy* specifying the dynamic relationship between the active entities that represent the Information System – the holons; this is the Information Model [5]; 2) Designing the *agent-based framework* to be used for the control architecture with distributed intelligence - defining the role of each information counterpart of physical entities: room and parameter conditioning models; control modes and laws; sensors and HVAC units; 3) Specifying the *switching modes* between hierarchical, centralized computing of the global facility model and environment parameter set points, and heterarchical, decentralized control of environment parameters at HVAC channel level [6].

In what concerns services, there has been a constant research effort to create principles for the orientation towards services of representative classes of processes such as control and manufacturing [7]. A thorough description of services in the industrial process control domain has not been yet formulated, nor their basic component set from which fractal processes can be derived.

Related to multi-agent frameworks for process control with distributed intelligence, [8] considers the dynamic changes of the client's needs which may require a smart and flexible automatic composition of more elementary services. By leveraging the service-oriented architectures and multi-agent system benefits, a method is proposed to explore the flexibility of the decision support for service reconfiguration based on trust, reputation and QoS models. This method is based on adding service attributes to agents, which allows including the agents' intelligent decision-making capabilities to change dynamically process parameters or resource operating modes, towards more trustworthy services with better quality when unexpected events occur. In the same con-text, [9] identifies various types of services such as: space-, time- and form- transformation services in control structures classified according to the active role of their related physical entities (e.g., environment tracking holons).

2. Modelling environment conditioning processes with EServices

2.1. Process classes and services in environment control

In the manufacturing value chain domain mixed batch planning and product scheduling are concerned with optimally scheduling the order of products entering the shop floor and operations execution on assigned re-sources, so that a global cost function is optimized (throughput, batch execution time, balanced resource loading, etc.) Process Planning Flexibility for manufacturing is added through semi-heterarchical control topologies in which an optimal sequence of processes is computed at centralized layer on global batch horizon and offered to the shop-floor control system as recommendation. Before applying the recommendation for product execution, the solution is checked against other possible ones by a group of intelligent entities (the holons) cooperating on the heterarchical, decentralized layer of the control system (Delegate MAS [10]). If a much better solution is found, it will replace the off-line computed one. The procedure applies at resource failure or degraded performance.

Similarly, in the environment process control domain, the HVAC operating modes, control laws and timing data (sampling intervals for data acquisition and control update) are off-line optimally configured so that the parameters: temperature, pressure, relative humidity and radiation in closed spaces for production, access halls and operator's office reach imposed values. Process Conditioning Flexibility (PCF) for environment control is added by dual control topologies in which set point values of individual closed spaces are first computed from the global facility model at centralized, hierarchical layer and then transposed in set points of the resources' conditioning parameters (air and cooling water flows of HVAC units) by a set of agents updating on the heterarchical, decentralized layer the HVAC process models, operating modes and channel references [11]. This means that environment conditioning parameter specifications are updated at discrete time intervals – the control's sampling periods, in order to maintain the facility's environment parameters in their normal operating ranges in the presence of disturbances, to redefine process models and control laws and to possibly reassign resource channels according to the quality of the services they have provided.

According to this concept, PCF results mainly from decoupling the global facility environment model from channel parameter conditioning processes, and distributing intelligence among several types of actors that take in common the best control decisions and execute them to satisfy a global facility goal. To reach PCF, environment control processes for large, multiple-space plants must be specified and designed with a certain degree of modularity. The development of Control Classes that group:

- Classes of control algorithms: feed forward, based on process models, observers;
- Types of control laws: linear-PID; nonlinear: hysteresis, predictive, sliding mode; optimal;
- Operating modes: cascade, fixed/variable structure, set point tracking, multitasking, event-driven data acquisition and control sampling,

adopted by HVAC manufacturers and automation companies for designing environment control systems is characterized by adding modularity to control processes in order to exploit the similarities existing between different control variants, to reuse validated control options and to provide the flexibility needed in reengineering environment monitoring and control systems according to clients' requirements. Such modularity added to the control structure allows decomposing it into groups of basic physical components having information counter-parts - the holons, and decoupling global facility models from channel parameter conditioning. These control blocks can be multiplied, interconnected and composed in variants of control systems corresponding to the global needs of any particular facility environment solution.

According to [12], similarities existing in a control class structure translate into certain commonalities in the process domain; this means that the common control characteristics can be mapped into features defining activities, processes and sequences of actions in the process domain. In consequence, there exists a process structure which can be associated to the above defined control structure in the information model of the control class; we can then introduce the concept of Process Classes related to environment monitoring and control applications, which is represented by a set of environment conditioning operations that, likewise to the concept of Control Classes, possess the attributes of modularity, similarity, cohesion, reutilization and scalability [13]. Such categories of processes for temperature, pressure and relative humidity regulation are:

- Heating/cooling coil processes with variable water flow admission;
- Variable fresh air changes / hour in clean rooms;
- Air flow admission (e.g., Variable Air Volume-VAV) and distribution (e.g., Variable Frequency Drives-VFD) of supply and exhaust fans;
- Air humidification, air filtering.

It becomes thus possible to apply the concept of services to environment conditioning process specifications, in the perspectives of: componentisation, representation as services with main attributes: exposing, discovering, negotiating, assigning, recomposing, standard interconnectivity and reusability.

This article introduces a modelling framework for PCF-type environment control services based on generic sensing, modelling and control process specifications that allow the customized design of a HECS control architecture.

The conceptual models of EServices and control processes preserve the fractal character of environment parameters and processes, and make possible the reutilization and composition of sets of various sensing, computing, modelling, control and monitoring operations, much similarly to the way products with required features are designed and manufactured in applications implementing the Product Families concept.

2.2. Representation and assessment of Environment Services in the holonic paradigm

Transposing the theory of services to environment conditioning processes and integrating the principles of ser-vices into holonic environment control leads to a new type of system: the Service-oriented Holonic Environment Control System (SoHECS), highlighting an information architecture allowing for repeatability and reusability of control operations. By adopting the SOA model for environment control, conditioning operations can be standardized into EServices exhibiting an unambiguous identification and complete description of both the interactions between the client (who ordered the product batch) and the service provider (the facility ensuring proper environment parameters for production and operator safety), see Fig. 1.

The relational EService model is subordinated to the concept of holonic control; three basic types of holons interact in a holarchy derived from the PROSA reference architecture: environment (room) holons, environment conditioning (task) holons and resource holons [14]. Expertise (staff) holons, having a global image of the plant’s environment conditions, requirements and control interdependencies treat room parameter data according to cascaded room models and assist the basic task holons in accomplishing their activity.

Every oval and rectangle in Fig. 1 which uses the class diagram of UML (Unified Modelling Language [15]) represents an entity type in the system, respectively a holon type and a data structure, whereas each line represents a relation. Depending on the symbol on the line - diamond, full arrow, arrow (not present in Fig. 1) or no symbol, the line refers to a different kind of relation.

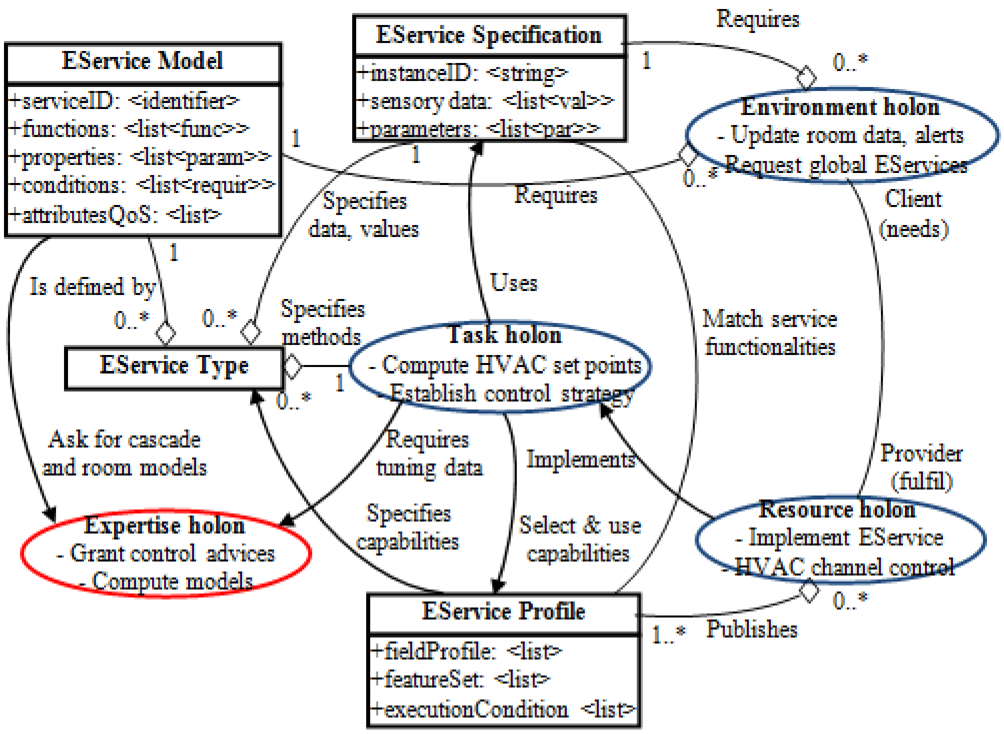

Fig. 1. Modelling the Environment Service (EService) from client-provider viewpoint

The aggregation relation (“has-a” relation) is indicated by a line with a diamond; for example, any EService Type has associated one model, a specification and a Task holon. The latter is created by selecting from the Profile data the best capability of that resource that fulfils certain conditions (cost, performances or utilisation time) better than any other resource, and best matches the requirements of the EService. The association relation (“is-related to” relation) is shown by a normal line; for example, the Environment holon type features a client-provider association with the Resource holon type. The directed action relation (“does-a” relation), indicated by a line with a full arrow, refers to a unidirectional action undertaken by one entity relative to another; for example, the Task holon type uses a EService specification to configure that EService. The cardinality of a relation is specified by numbers placed at both extremities of the line (0..*, 1..*, 0..1, 0, 1, or unspecified), and represents the number of this type of entities that are involved in the relation. The diagram in Fig. 1 shows that a Resource holon type has at least one EService profile or set of capabilities allowing the delivery of that simple or composite service.

The structure of the HECS architecture is built around the three types of basic holons interacting in a holarchy structure. A more detailed specification of these holons is given by their data- and functional models which extend the class model in Fig. 1. The mapping of data and functions to the three basic holons and the expertise holon is described below:

- **Environment (Room) holons, EH**: formulate EService requirements; they contain a physical part represent-ed by the set of sensors that measure the environment parameters, some of them vital for the product's quality while others may be critical for the safety of humans and material assets. They contain also an information processing part, represented by data acquisition and primary processing (linearization, compensation, unit conversion, in-range limit checking, averaging, fault-tolerant transmission) software programs that monitor environment parameters. Room holons hold parameter knowledge assuring the safe making of products in processes with imposed cleanness; they contain the "safety and quality model" of the product's environment, in terms of "cleanness compliance". EH check against prescribed values the environment parameters (e.g. temperature, pressure, etc.) measured in all closed spaces, send the data to the Expertise holon(s) and the request to perform the necessary EServices for the entire plant.

- **Task (Environment conditioning) holons, TH:** configure the control EServices at HVAC channel (resource level); they represent tasks that select and update control modes, strategies and laws, timing for the control, handling of exceptions and alarms and compute the set points for the HVAC channel controllers that regulate the environment parameter conditioning process. A Task holon can be interpreted as single-channel "environment conditioning order", manages the execution framework and specifies how this task is accomplished and its effects. Task holons deliver to Resource holons the parameter conditioning knowledge from updated environment data, acting as short term schedulers for environment conditioning operations.
- **Resource holons, RH:** implement EServices; they contain a physical part which is the environment conditioning resource - the HVAC unit, and an information processing part that controls the resource (e.g., a remote terminal unit – SCADA, a model-based device controller). This entity holds the techniques to allocate the environment conditioning resources – the cooling water and fresh air conditioning modules (filter, heating / cooling coil, humidifier, fan), and the knowledge (operating modes and control procedures) to activate these resources to maintain at channel level the updated environment conditioning set points.

- **Staff (Expertise) holons, SH:** coordinate EServices at global level; they correlate the set of room parameter references by using their global knowledge about the plant's aggregate environment models, and transfer these correlated set points to the Task holons. They formulate also recommendations to Task holons to update control modes (at seasonal changes) and tune control laws (at decreased quality of EServices).

The basic and Expertise holons exchange knowledge in the semi-heterarchical SoHECS about the processes they have to perform accessing and using from different viewpoints the EService instances as shown in the class diagram of Fig. 1: EService Type, EService Model and EService Specification. With knowledge retrieved from these information-oriented instances, the Task holon creates and implements the EService by selecting resource capabilities that best match the desired service functionalities and characteristics; these capabilities are published by Resource holons in the EService Profile data structure.

In the centre of the class diagram in Fig. 1, the EService Type identifies a service included in an existing service-ontology about environment conditioning and control. This data structure lists the proper-ties that characterize an instance of that same service type, to further set up a certain EService Specification: name, category, type of parameters, inputs, outputs. The EService Model instance specifies the components of an EService. An EService Specification defined by the client (the conditions to be met by the environment facility for the production processes) is associated as an instance to an EService Type providing information on the values of its properties and making service requests. The HVAC resources, as service providers, publish their control capabilities in the EService Profiles data structure, thus exposing their transformation capabilities to the Task holons in view of being assigned services. Hence, the EService Profile of a resource specifies the set of field characteristics, range of parameter values and performances for a certain EService Type that this resource can deliver according both to its design, technology, technical performances, and to its current state, wear, and availability derived from maintenance schedule. The selection of the resource's EService Profile best matching a unique set of needed EService Specifications results from a many-to-one comparison of associations between the services that can be provided and the requested one.

The setup of an EService, i.e. configuring by which resource and how the service will be executed - according to the selected EService Profile, is performed by an Environment conditioning holon, whereas the implementation of this EService is done by the Resource holon's physical part (the HVAC channel) controlled by the RH's agent. The Task holon transposes the selected EService capabilities set into the necessary control mode, law and parameters to produce the transformation described by the associated EService Type.

2.3. Configuring and implementing EServices

The **EService Model** includes the property fields that define environment conditioning or control processes, assessed as services, in the client-provider perspective of global facility environment monitoring and control. The structure of an EService is represented by the model shown in Fig. 2. This model can be created for any EService Type to be used in aggregate environment control applications from an environment monitoring and control domain service-ontology, by specifying its components that describe that EService.

The EService is identified by a ServiceID which is composed by four fields: 1) a name, 2) the class to which it belongs (e.g. parameter conditioning, parameter control), 3) its taxonomy, and 4) the service ontology in which it is referred. The second property field describes in text file the Functions performed by the EService in terms of: scope, context of execution and tasks to be realized. The third property field, Service Properties features the list of parameters which specify completely the EService: the actions or processes to execute, the execution timing (sampling frequency, duration) and the information support used for execution (process models, operating modes, computing results, etc.).

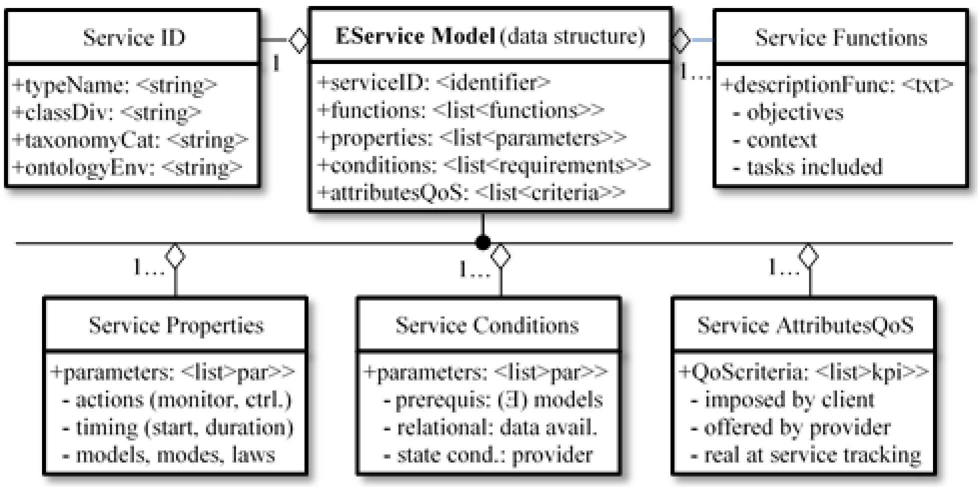

Fig. 2. Components of the EService Model

Service Conditions denote the fourth property field of the EService Model; it accounts for several attributes that must be satisfied by the provider or other agents prior to service execution: 1) prerequisites, such as the existence of updated process models, 2) relational conditions, such as data availability (e.g., set point for HVAC channel parameters already computed by Task holons), and state conditions, such as the provider's operational state. The last of the property fields is Service AttributesQoS which lists key performance indicators (KPI) to be initially specified (at service request and offer) or computed at run time to evaluate the foreseen quality of ser-vices (QoS), respectively that of delivered ones. For a SoHECS service-ontology, KPIs will be defined both at global (rate of class cleanness maintenance during product making, rate of maintaining room environment parameters in normal value range relative to the global cascade model, a.o.) and local (accuracy of the HVAC channel parameters matching computed set point values, control loop asymptotic stability, a.o.) level.

3. Multi-agent implementation of EServices

As defined in chapter 2, the holonic facility environment control paradigm is based on defining distributed sets of basic holons communicating and collaborating in a holarchy to put in practice strategies and rules established by higher level expertise holons to reach a common goal at production facility level. By help of agents – the holons' information counterparts – it is possible to solve at informational level the environment conditioning tasks that are configured, selected, composed, assigned to the holons' physical parts as services and evaluated for their quality. Hence, the inherent distribution of control intelligence of the MAS implementation framework according to predefined and selected environment ontology can be transposed in the physical realm.

Agents in the MAS are service-oriented to allow reconfigurability, flexibility and interoperability in an environment control heterarchy; this requires the implementation of several features through collaboration and negotiation, such as service-discovery, service-registration, service-composition and service-reconfiguration, from which the last one is crucial to facilitate the changes needed to compensate for disturbances in the monitored production environment.

Although the EService Implementation is a process realized in principal by the Resource holons' agent part, several types of information entities participate in the instantiation stages of the EService Model (Fig. 3):

1) *Integrating the EService specifications* formulated by the client environment application in the global, cascaded environment parameter model of the SoHECS;
2) *Matching the functionalities* of the requested service, expressed in the parameter values of its properties, conditions and attributes, with the capabilities exposed by resources in their EService Profiles;
3) *Assigning the resource* with the best matching field profile set and confirmed quality of already delivered services to implement the needed EService;
4) *Reconfiguring the service provider* in the case of resource breakdown or degraded QoS.

A Task agent is created whenever a client environment application EService request is issued at SoHECS initial configuring, from data progressively stored in the EService Type structure: i) client application data provided by Room agents, aggregated according to the global model of the facility environment, and ii) a number of field profile sets provided by Resource agents; these sets could be possibly used to implement the requested EService.

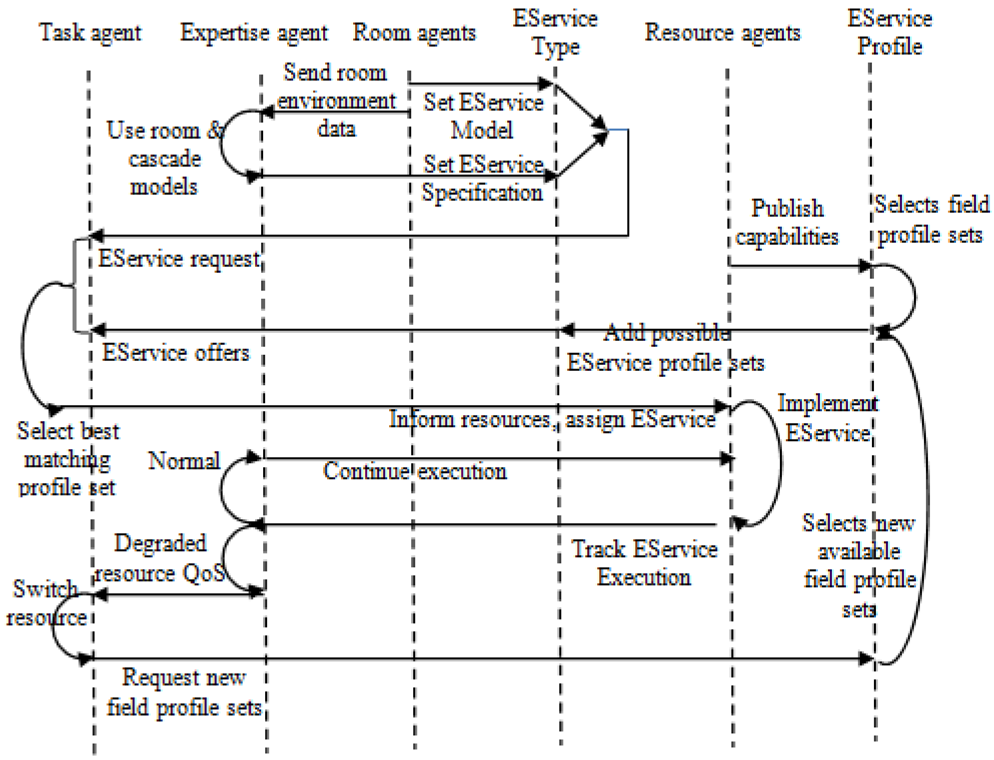

Fig. 3. Agent-based resource selection and EService implementation

All field profile sets are a priori published by Resource agents in dedicated repertoires of the EService Profile data base from which, upon request, only the subset of profiles possibly matching the client EService is added to the EService Type data structure. Each one of these subset profiles contains detailed information on the process methods, laws, models and technology (sensing, monitoring, control and interfacing with humans) that implement the transformations specified by the client EService Model and Specifications. Process methods describe a sequence of actions (e.g., transfer of HVAC channel set point values, model-based channel process control, PID parameter control, channel environment parameter conditioning) that transform/maintain the environment parameter specified by that EService Type. Process methods can be associated with three types of process models according to their functionality and composition rules: 1) computational model, 2) simple / composite control model, and 3) channel / global environment conditioning model. According to its cardinality indicated in Fig. 1, a resource may have more than one method achieving the same transformation which the resource's agent publishes in the EService Profile data base.

The Task agent establishes the field profile in the subset offered from the EService Profile best matching the specifications of the requested EService, informs all Resource agents having participated in this bid about the decision taken, and configures the selected resource in view of implementing the EService with the chosen pro-cess method. The decision support for this selection is granted in centralized mode by one Expertise agent.

The execution of the EServices by the allocated resources is monitored by Task agents; if the quality of the service delivered by a resource drops down or a resource breakdown is detected, then an initiative is taken to reassign the EService to another available resource that possesses the needed capabilities in a selection process similar to the above described, but in pure heterarchical mode [16].

The decisional part handling EServices according to the holonic environment conditioning and control paradigm is implemented by a multi-agent system with distributed intelligence for data communication, multi-stage processing and decentralized decision-making. Each agent executes on its associated hardware, as in Fig. 4.

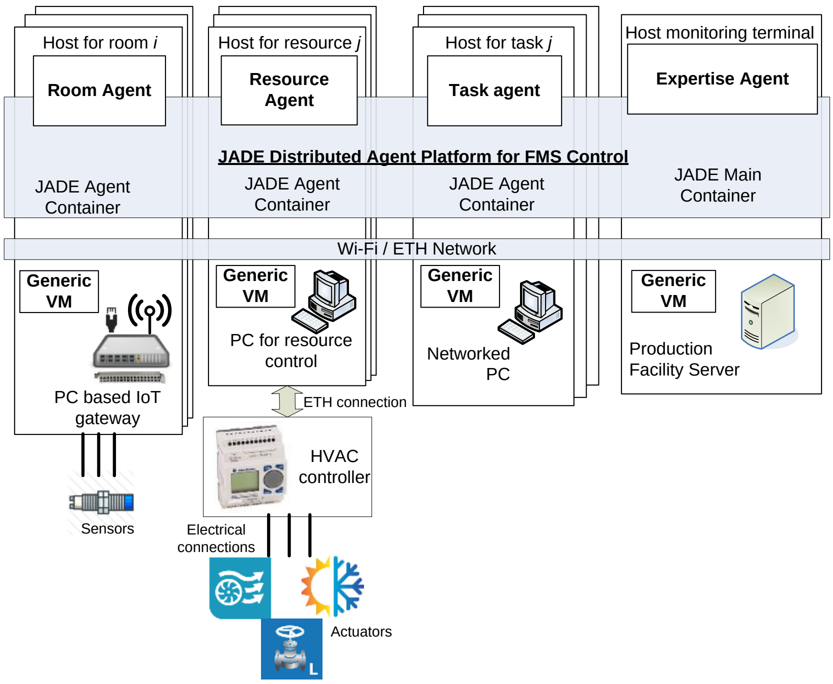

Fig. 4. MAS framework implementing the holonic environment control system based on EServices

For the implementation of the MAS, the Java Agent Development Framework (JADE, [17]) is used as it complies with the FIPA standards for intelligent agents (www.fipa.org): communication and interaction protocol standardization through the agent communication languages (FIPA-ACL) used in holon communication, and simple behaviour definition used in holon decision-making. The four types of agents composing the architecture in Fig. 4 execute on generic hardware units as follows:

The Room agents are located on IoT gateway processors that integrate the sensors measuring environment parameter values in the facility's spaces into the IT network used for monitoring and control. The role of these agents is to collect sensor data and offer it to the MAS in a standardized manner. Each production room - clean rooms: cyclotron, synthesis module, dispenser and quality control lab, and their access spaces has an associated room agent collecting and processing in real time at low level environment data from all sensor sets (temperature, pressure, relative humidity, airborne particles and radioactivity).

The Task agents are located on the networked PCs of the environment control system of the production facility. Since the task agents provides reference values for the resource channel agents there is a single replicated Task agent for each Resource channel agent.

The Resource agents represent from the informational point of view (monitoring, providing set points values, changing control modes) the resource channels used in effectively regulating the environment conditioning parameters of the facility's closed spaces. The resources are represented by Heating, Ventilation and Air Conditioning (HVAC) automated devices. The Resource agents are located on the PCs associated to the HVAC equipment, their role being to integrate locally the HVAC automatic control layer with the distributed MAS global decisional layer.

The Expertise agent is located on the high availability cluster consisting of PCs linked via Ethernet to the re-source controllers and the cell server – head of the cluster. Its role is the aggregation of data obtained from the Room agents using global facility environment parameter models and the computation of local (room) reference values for these parameters. There is a single replicated expertise agent which centralizes data.

By using the JADE framework, it is possible to replicate all agents in order to have a fault-tolerant platform.

Concerning the communication layer all devices are interconnected at physical level through a combination of wired (Ethernet) and wireless (WiFi) network which supports a TCP/IP communication protocol. On top of the communication protocol the JADE framework offers a set of high-level interaction protocols which are based on message exchange according to the FIPA ACL standard (www.fipa.org).

4. Holonic environment control of radiopharmaceuticals production: experimental results

Radiopharmaceutical substances with specific chemical structure, radioactivity and purity are obtained in 4-stage manufacturing processes: 1) radio isotopes are produced in a particle accelerator (cyclotron); 2) the irradiated bulk substance is subject to chemical synthesis in a technology isolator; 3) the synthesized bulk product is eventually diluted and portioned in vials in the dispensing room; 4) quality control is done on sample vials containing the final product; products are then packed and transported to clients in shielded containers.

During the production stages, special conditions must be permanently fulfilled; these conditions are: radio-protection safety conditions (radioactivity doses, pressure cascades and number of air changes per hour in clean rooms) and environment manufacturing conditions as defined by Good Manufacturing Practice (GMP) guides [18].

The cleanliness monitoring system uses a laser airborne particle counter which is placed in the dispensing clean room. The number of air particles inside the hot-cell is constantly monitored so that the number of 0.5µm / 5 µm-size particles detected in the extracted air samples must be less than 3520/20 (Table 1).

The room parameters are read at different sampling time periods; once an alert is raised for at least one of P, T and RH, production continues and simultaneously appropriate actions are initiated to bring back their values within the range corresponding to the normal state; if these actions have not effect and the alarm state is entered, production is stopped. The same decision is taken when the level of radioactivity expressed by the parameter H_c^* (10) enters the alert value range. A special situation is generated when the number of airborne particles in the dispenser isolating box, NP_c exceeds the predefined alert value; in this case, two decisions are taken:

- Dispensing of the bulk radiopharmaceutical product (already irradiated and chemically processed) is temporarily suspended. This decision is taken upon detecting that the number of airborne particles exceeds the upper limit value of the class A normal range (3520 particles of 5µm/20 particles of 0.5µm).
- The rate of air changes (admission of fresh airflow, evacuation of impure air) is increased in the HVAC unit connected to the dispensing isolator box, to eliminate as much as possible airborne particles.

If the value of the NP_c parameter re-enters the normal state in less than 20 min., dispensing is started or resumed. Otherwise, the process is definitively stopped, and the current production is cancelled. Depending on the recovery time for NP_c, some of the remaining product orders for that day will be re-planned.

Whenever the number NPc of airborne particles measured in the dispensing room enters the alert state, the MES is instructed by the SoHECS to suspend the dispensing process for maximum 20 min, time in which the EService for air conditioning in the dispensing room is reconfigured as follows: the command frequencies of the VFDs for the supply/exhaust fan are increased to create higher overpressure in the cleanroom, and the rate of air changes (admission of fresh airflow, evacuation of impure air) is increased in the HVAC connected to the dispensing isolator box to eliminate particles in the shortest possible time. If, despite these corrective actions NPc does not re-enter its normal state in less than 20 minutes, dispensing is stopped, and production is abandoned.

Another important function of this decision EService is to recalculate the post recovery volume of diluter per vial, for the remaining volume of product to be dispensed after NPc re-enters its normal state; the VDPR volume is calculated considering the irradiation level of the bulk product measured at the time of cleanness recovery, TCR, and is smaller than the initially planned volume of diluter per vial, VDVP.

The corresponding set of services is: i) suspending the production process, ii) reconfiguring the air condition-ing process, iii) recalculating the product recipe for vial filling, and iv) resuming the dispensing process form a composite production influencing EService that is initiated by NPc entering the alert state.

Table 2

Cleanness alert event generated in the dispensing room and production influencing EService (NPc alert value = 3520 (0.5 µm) / 20 (5µm); cleanness recovery time = 6 min 26 s; less diluter per vial)

Event/State	**Time** hh:mm:ss	**VFD parameters** Fs/Fe [KHz]	**VAV parameters** P[Pa], NAC[#]	**Measured NPc** NPc (0.5 µm/5µm)
Normal, VDVP = 22% vial volume	09:12:00	32KHz/20KHz	25 Pa, 20	3220/12
25 min	…	...	…	…
Normal	09:37:00	32KHz/20KHz	25 Pa, 20	3260/14
Turn off HVAC	09:37:00	-	-	
5 min	…	-	-	3890/42
Alert NPc Request EService Turn on HVAC	09:42:00	38KHz/28KHz	-	3890/42
6 min 26 s	…	…	…	…
Cleanness recovery Measure IRPR Recalculate VDPR (20% vial volume)	09:48:26	38KHz/28KHz	35 Pa, 25	3480/18

Experiments have been carried out to evaluate the correct design and implementing of the composite decision-making and production influencing EServices of the type above described. Table 2 shows the results of an experiment, when an alert situation for NPc was generated to trigger the reconfiguring of VFD and VAV air conditioning processes and the recalculation of product characteristics in vial dispensing.

Several cleanness recovery experiments were performed in the plant's clean rooms; among these, a recovery time test for HVAC VFD performance in reducing particle concentration in the dispenser room. ”Recovery time” is defined by ISO Standard 14644-3 as the time required to reduce a currently increased particle concentration in a “class A” clean room up to the “normal state” value range [19].

A laser particle counter PMS model Lasair III 310C was placed inside the dispenser. When the clean room was in “work state” with the HVAC system running and the dispenser ready for daily production process, the particle counter was started. The first read after 1 minute indicated 3220 particles (0.5 µm) and 12 particles (5 µm), within the limits imposed by GMP specification. The HVAC VFD for supply fan/exhaust fan were set at 38 kHz/ 26 kHz; an overpressure of 35 Pa was thus created inside the cleanroom, with the airflow set up to provide 20 air changes/hour (the number of times the air enters and exits a room from the HVAC system in one hour). The HVAC system was then turned off for 5 minutes and then switched back on showing 4870 particles (0.5 µm) and 80 particles (5 µm). After 20 minutes functioning time, the particle counter displayed 3410 particles (0.5 µm) and 16 particles (5 µm), meaning that the radiopharmaceuticals dispenser has successfully recovered its “A grade” cleanliness.

This sequence was repeated for HVAC supply/exhaust fan set at 32 kHz/20 kHz and overpressure of 25 Pa created inside the clean room with an airflow set up to provide a number of 10 air changes/hour. After 5 minutes switch off the number of particles was 4860 (0.5µm)/78 (5µm), and then, after 20 minutes the values shown by the particle counter were 4630 (0.5µm)/40 (5µm), meaning that for 10 air changes/hour the dispenser was unable to recover its “A grade” class. With these last settings, the recovery time was 43 minutes – unacceptable for routine production. From these experiments it was concluded that higher supply air flows and implicit a higher number of air changes/hour significantly reduce the dispenser's recovery time. The task holons can impose different setup coefficients for the two RTU SCADA controllers, so that VFD will operate at higher frequencies until the cleanliness class is successfully restored, and then restore its normal settings to avoid high energy consumption.

5. Conclusions

The article introduces a framework for designing flexible Environment Control Services (EServices) based on generic sensing, modelling and control process specifications that allow customizing and on-line reconfiguring the control architecture function of the: i) facility layout, ii) temperature, pressure and relative humidity models of closed spaces (clean room, access space, personnel office), iii) global facility environment model - if any, iv) heat and ventilation channel parameter model - HVAC process model, v) imposed performance characteristics of automated systems - stability, efficiency, robustness, response time, a.o., and vi) control strategy, operating mode and control law of the HVAC controller.

There have been defined four types of processes: environment monitoring, control, conditioning and production influencing, represented in the service perspective either as simple or composite services according to timing progression, granularity and concurrency of their operations set.

By adopting the service-oriented model and information architecture for environment monitoring and control, environment conditioning operations are standardized as EServices allowing creating flexible, reactive, reconfigurable and robust systems for aggregate environment parameter conditioning of multiple interrelated spaces. The relational EService model proposed is subordinated to the concept of holonic control; three basic types of holons interact in a holarchy inspired from the PROSA reference architecture, getting expertise advice from staff holons which have the global environment knowledge at facility level.

The advantages of using a model-based environment monitoring and control system with intelligence distributed by agents are: flexibility in adopting the environment control strategy (at centralized level) and applying it at facility room level through task configuring, decoupling process execution from the physical structure (sensors, HVAC), high availability through semi-heterarchical control mode and fast recovery times at disturbances altering the environment of the clean rooms.

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