EnerMan

Energy Efficient Manufacturing
System Management

D2.4 - EnerMan Edge Flexible, Adaptable, Control Loop Support

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EnerMan

Short Description
As part of the second Work Package (WP) of the EnerMan project, this deliverable relates to Task T2.3. This task focuses on supporting the design of the Cyber Physical System (CPS) distributed control loop mechanism. This deliverable (D2.4) aims to propose methodologies for the design of a flexible and adaptive control loop, primarily focusing on edge equipment (WP2 being responsible for the development of the data collection and processing regarding edge devices). This deliverable first provides an analysis of control mechanisms currently implemented in the different EnerMan use cases (section 2). Then, an ontology-based control loop mechanism is proposed (section 3). A control-oriented HVAC simulator is implemented (section 4) and used to virtually test diverse control strategies and compare their performances, regarding energy consumption in particular (section 5).

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EXECUTIVE SUMMARY

This deliverable summarises the work that has been carried out as part of Task 2.3.

As part of the second Work Package (WP) of the EnerMan project, this deliverable relates to Task T2.3. This task focuses on supporting the design of the Cyber Physical System (CPS) distributed control loop mechanism. This deliverable (D2.4) aims to propose methodologies for the design of a flexible and adaptive control loop, primarily focusing on edge equipment (WP2 being responsible for the development of the data collection and processing regarding edge devices).
This deliverable first provides an analysis of control mechanisms currently implemented in the different EnerMan use cases (section 2). Then, an ontology-based control loop mechanism is proposed (section 3). A control-oriented HVAC simulator is implemented (section 4) and used to virtually test diverse control strategies and compare their performances, regarding energy consumption in particular (section 5).

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GLOSSARY OF ACRONYMS

Acronym	Definition
AHU	Air Handling Unit
API	Application Programming Interface
DRL	Deep Reinforcement Learning
DUL	DOLCE+DnS Ultralite ontology (in this context, Dolce-Ultralite Alignment Module, an extension of the SSN ontology) http://www.w3.org/ns/ssn/dul
EMS	Energy Management System
EnPI	Energy Performance Indicator
FL	Fuzzy Logic
FTC	Fault-Tolerant Control
HVAC	Heating, Ventilation, and Air Conditioning
iDSS	EnerMan's intelligent Decision Support System
KPI	Key Performance Indicator
MPC	Model Predictive Control
OWL-S	OWL-S ontology: Semantic Markup for Web Services http://www.w3.org/Submission/OWL-S
PID	Propotional-Integral-Derivative controller
PLC	Programmable Logic Controller
RL	Reinforcement Learning
RMS	Root Mean Square
SCADA	Supervisory Control and Data Acquisition
SOSA	Sensor, Observation, Sample, and Actuator ontology http://www.w3.org/ns/sosa/
SSN	Semantic Sensor Network ontology http://www.w3.org/ns/ssn/
W3C	World Wide Web Consortium (main international standards organisation for the World Wide Web)
WP	Work Package

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1. INTRODUCTION

A first objective of this deliverable is to propose an implementation strategy for providing control on machinery or propagating automation sequences to legacy equipment, e.g., Programmable Logic Controllers (PLC). An *EnerMan intelligent CPS end node* is developed throughout WP2; the D2.4 deliverable focuses on the definition of a bi-directional data flow between the intelligent CPS end node and the machines and sensors in the factory. The CPS end node must therefore be compatible with the factory automation control toolboxes, with appropriate interfaces supporting industrial protocols for control signal transmission. It should be noted that, for sensitive production processes or specific pieces of equipment, automatic transmission of control configuration should be avoided. With a view to allow operators or engineers to act on recommendations originated by the EnerMan system and the intelligent Decision Support System (iDSS) in particular, human-in-the-loop should thus be enabled.

As a first step, a mapping of the existing control mechanisms currently implemented in the EnerMan use cases is proposed (section 2). This use case analysis is based on questionnaires passed on to experts at the industrial partners' companies, and relevant information exchanged over technical meetings. As such, it cannot be exhaustive, yet this executive summary about the current practices and pieces of equipment aims to ease future integration tasks with regard to EnerMan components.

An ontology is then proposed, together with an implementation blueprint ensuring the consistency of the representation. This provides a semantic analysis easing the specification of the control feedback interface between EnerMan and plant systems. The concepts and relationships that form the ontology were chosen among industrial standards, as will testify a literature survey on this subject in section 3.1. The proposed ontology allows the formal representation of use cases (i.e., legacy equipment and available software) as well as EnerMan components (iDSS, end node, etc.). The ontology also provides the opportunity to check the applicability of an EnerMan subsystem, e.g., for pre-validating the implementability of the Kalman-based prediction engine (Task 4.2) or the uncertainty-aware prediction engine (Task 4.4). This verification mechanism is illustrated in section 3.4 with a control algorithm to be implemented in a simple use case.

Another important aspect relates to the control law and strategy to be considered in a use case. Nowadays PLCs can support multiple control laws, and by interconnecting several PLCs together, centralised control strategies, aware of physical dynamical couplings, can yield better performance than traditional control strategies (e.g., PID controllers implemented locally on each machine). In order to ease control law or strategy preliminary assessment, a simulator of the AVL TB403 use case is proposed. This simulator considers only physical aspects (temperature, humidity, energy-related variables, etc.) and allows to test different control strategies and to compare their performances, as presented in section 5.

In this deliverable, a use case analysis is developed in section 2, an ontology-based control loop mechanism is proposed in section 3, and a control-oriented HVAC simulator is presented in section 4. Finally, diverse control strategies are exposed in section 5.

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2. USE CASE ANALYSIS

2.1. Analysis approach

This section focuses on the description of the control mechanism **currently** in place in factory automation. Two technical questionnaires have been forwarded to use case owners, as part of Tasks 1.2 and 1.3 of the EnerMan project. Additional questions relate to the control and communication aspects of the use cases, including: equipment specifications and layout, as well as control input, objectives, and constraints. Six main questions have been formulated (the template is provided in APPENDIX A: Technical questionnaire on use case architecture):

1. Which KPI do you use or intend to use? (both for production and energy performance)
2. What sensors and actuators are available in this use case?
3. For each actuator (or group thereof), what is the current control strategy? (including control parameters)
4. What are the specifications of the controllers in place and how do these connect to the sensors and actuators?
5. Is there a supervisory control and data acquisition system (or a higher-level equipment network of some sort), and to which PLCs is it connected to?
6. For each SCADA / PLC, is there an API the EnerMan system could use in order to retrieve and pass on information?

Weather forecasts provided by local weather channels/websites are also of interest, although not compulsory for integration purposes. For instance, external environment conditions (e.g.: temperature, humidity) could be necessary to provide optimal control of specific actuators (as climate control system). When external conditions are not directly measured by the existing manufacturing system, weather data could be an interesting alternative. This question is not mandatory to meet T2.3 objectives but its answers would help to propose optimal control strategies.

Answers to this questionnaire have been synthesised in the following subsections and highlight the diversity of the control mechanisms in factory automation within the EnerMan consortium.

In the framework of this task, EnerMan use-cases can be classified into three main categories:

- Heating and Cooling process (CRF, YIOTIS, STN)
- HVAC system (CRF, AVL, DPS)
- Co-/tri-generation plants (ASAS)

The control inputs, objectives and constraints, and their physical implementation, i.e., legacy equipment and communication protocols that are currently involved in EnerMan use-cases (UC) are presented hereafter. This section focuses on current control strategies and control communication. For this reason, only use cases with control capabilities (requiring an action from the EnerMan system) are considered. Other use cases rather focus on process scheduling and energy monitoring, thus emphasising upstream rather than downstream data flow, i.e., these use cases will require data collection but little to no control capability from the EnerMan system.

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2.2. Current control strategies: Control inputs, objectives and constraints

2.2.1. *Heating and Cooling process (CRF, YIOTIS, STN)*

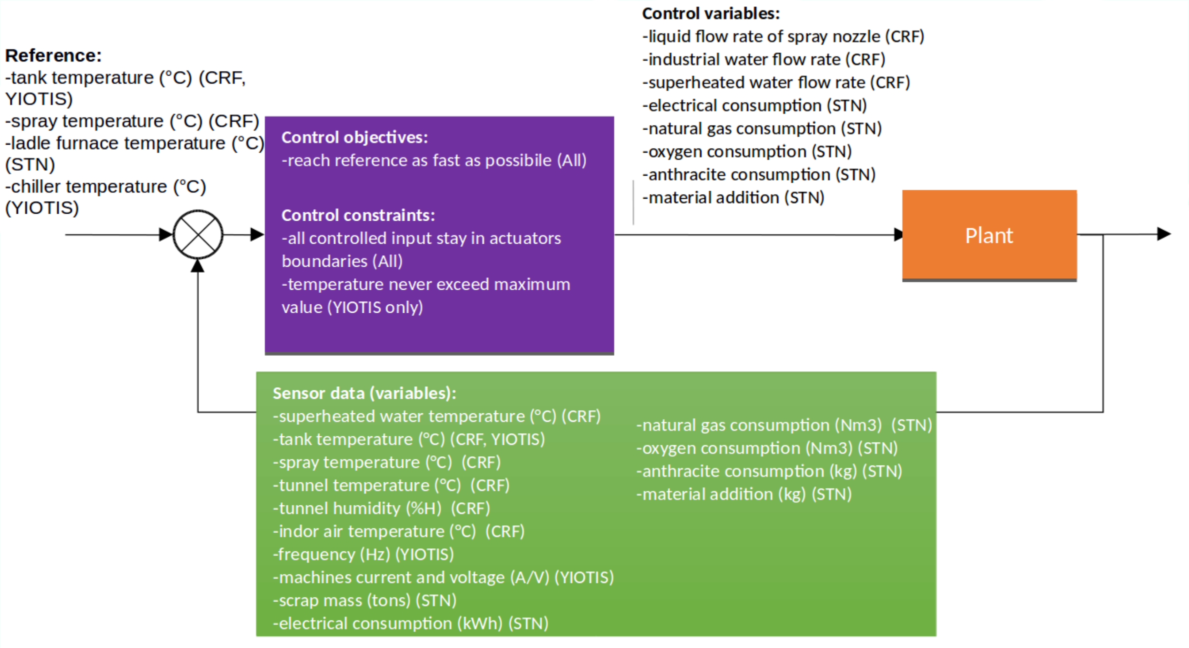

Figure 1 current control practices for heating and cooling processes: references, control variables, objectives (production-wise) and constraints, and sensors

<u>**Control inputs:**</u>

- **Reference:** Tank temperature, spray temperature (CRF degreasing tank), Ladle Furnace Temperature (STN), chiller temperature, storage tank temperature (YIOTIS)

- **Control variable:** liquid flow rate of spray nozzle, industrial water flow rate, superheated water flow rate (CRF degreasing tank), electrical consumption, natural gas consumption, oxygen consumption, anthracite consumption, material addition (STN). <u>No information available at the moment about control strategies of YIOTIS use case process.</u>

- **Sensor data:** superheated water temperature, tank temperature, spray temperature, tunnel temperature (over the tank) and humidity, indoor air temperature (CRF degreasing tank), frequency, current and voltage of machines (YIOTIS), scrap mass, electrical consumption, natural gas consumption, oxygen consumption, anthracite consumption, material addition (STN)

<u>**Control objectives:**</u> reach reference as fast as possible (CRF degreasing tank, STN). <u>No automatic control used for YIOTIS process (maintain temperature at constant value, alarm raised when values varies, to be confirmed).</u>

<u>**Control constraints:**</u> All controlled inputs stay in actuators boundaries (CRF degreasing tank), no temperature over 55°C (YIOTIS process).

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2.2.2. *HVAC system (CRF, AVL, DPS, YIOTIS)*

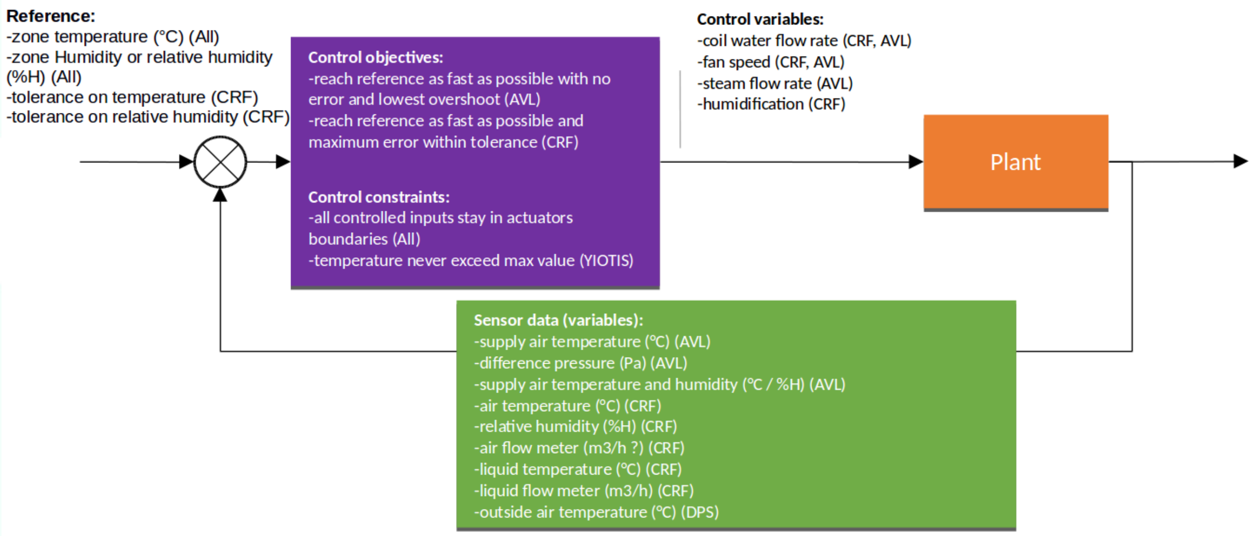

Figure 2 current control practices for heating and cooling processes: references, control variables, objectives (production-wise) and constraints, and sensors.

<u>**Control inputs:**</u>

- **Reference:** Humidity level, zone Temperature (AVL), Temperature, relative humidity, (CRF AHU), Temperature and humidity (DPS), room's temperature and humidity (YIOTIS production area)

- **Control variable:** coil water flow rate, fan speed, steam flow rate (AVL), coil water flow rate (superheated and chilled water), humidification, fan speed (CRF AHU). <u>No information available at the moment for DPS and YIOTIS use cases.</u>

- **Sensor data:** supply air temperature, difference pressure, supply air Temperature and humidity (AVL), air temperature and relative humidity (outdoor, booth, inlet and outlet heat recovery wheels), air flow meter, liquid temperature, liquid flow meter (CRF AHU). <u>No information available at the moment about installed meters (except communication protocol) of DPS use case. No information available for YIOTIS use cases.</u>

<u>**Control objectives:**</u> Reach reference as fast as possible with no error and lowest overshoot (AVL), reach reference as fast as possible, error within tolerance (CRF AHU). <u>No information available at the moment about control objectives for DPS AHU and YIOTIS production area.</u>

<u>**Control constraints:**</u> All controlled input stay in actuators boundaries, area temperature and humidity stay in defined boundaries (AVL, CRF, DPS). Another constraint is imposed for YIOTIS use case: temperature never exceeds maximum value (55°C).

2.3. Current equipment and protocols

The technical questionnaire focusing on control architecture (APPENDIX A: Technical questionnaire on use case architecture) consists of tables; this is presented so each table can be converted into a bipartite graph and supplemented with relevant node features (system capability, e.g., maximum sampling frequency, etc.) and edge features (e.g., control signal transmission protocols, etc.). The network architecture is briefly wrapped up in Figure 3 on the CRF and AVL use cases.

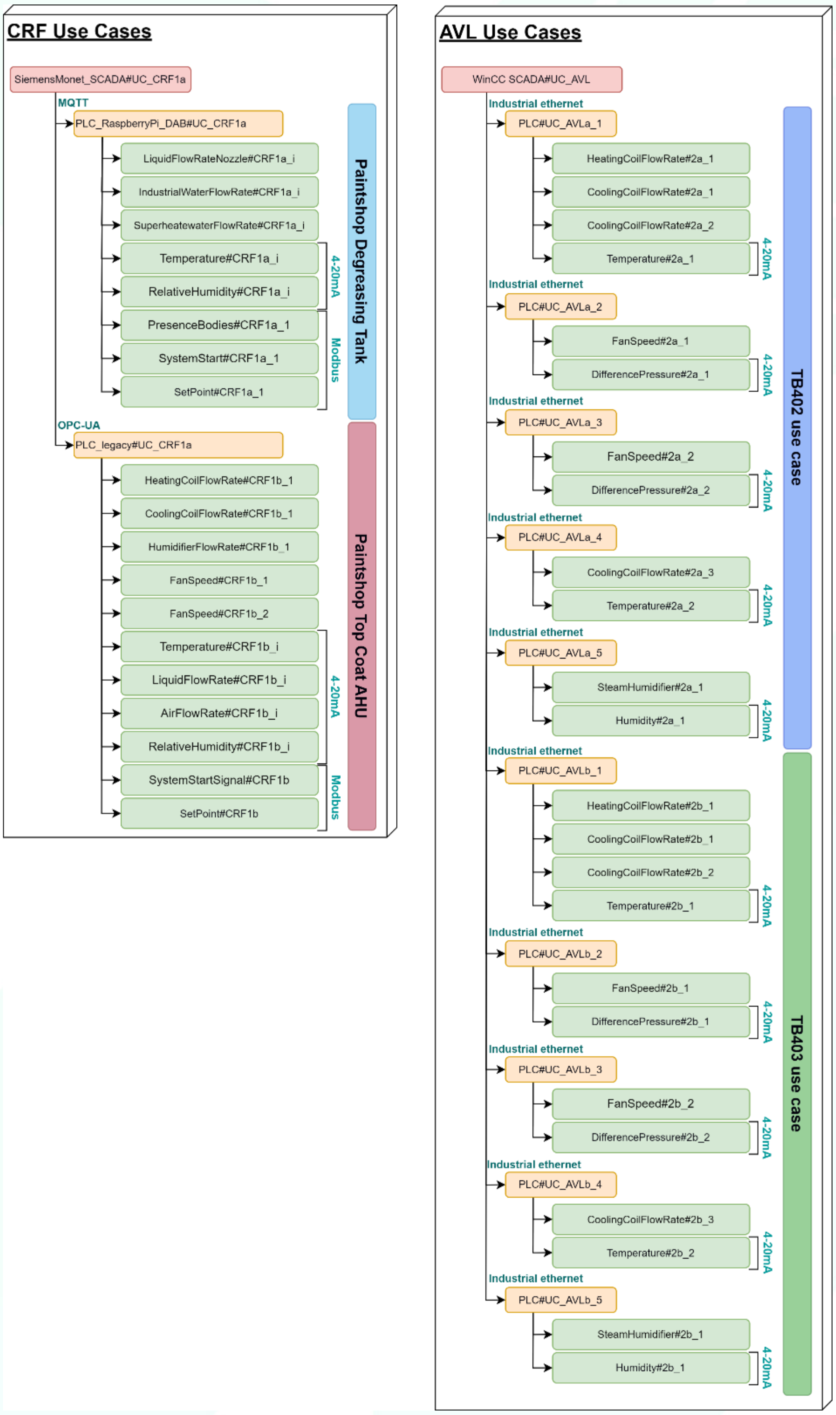

Figure 3 Control communication identity cards (i.e., network architecture and protocols) for CRF and AVL use cases.

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3. CONTROL LOOP MECHANISM SUPPORT: INTERFACE SPECIFICATION

3.1. Approach overview for interface specification

The EnerMan project provides 8 industrial use cases (**IUC**) on which the different development modules of the EnerMan framework (Data Collection, Control loop Configuration, Simulation Engine, Prediction Engine, Big Data analytics, iDSS Visualisation), as presented in Figure 4, have to be prototyped and then validated. In Task 2.3 and this deliverable D2.4, we focus on the control configuration loop module in order to propose an approach that allows to interface any type of control strategy (from the iDSS) to any manufacturing system.

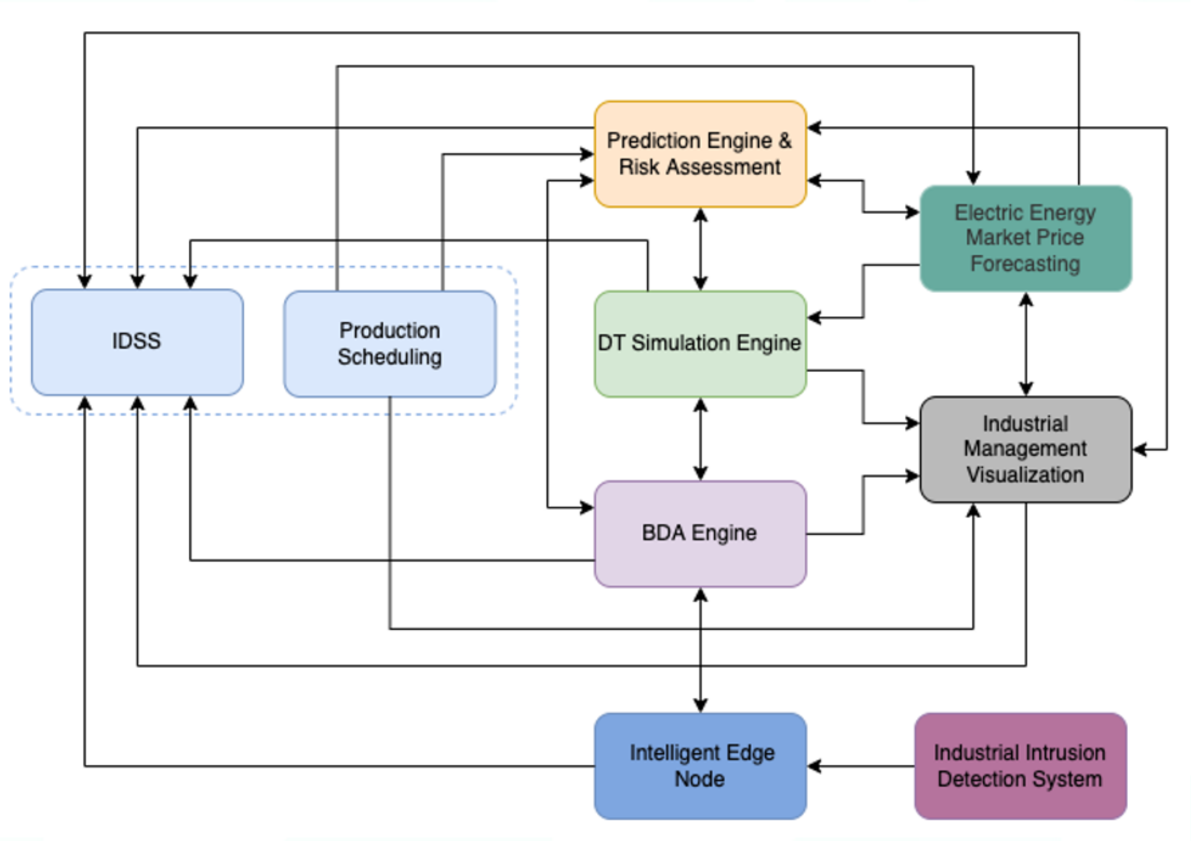

Figure 4 Main modules to be developed in the EnerMan System

Appropriate solutions have to be developed to collect data from the manufacturing systems to the different EnerMan modules, but also to propagate the configuration instructions and adaptations from the EnerMan system to the legacy machines. They should support the necessary compatibility with the existing factory automation control toolbox. Therefore, we need to identify the interfaces' compatibility between the EnerMan modules and the industrial protocols in order to support control signal transmission. As a result, a suitable modelling of the control mechanism is required so that the control sequence specified by the EnerMan system is mapped properly in the devices deploying these configurations.

In this context, the objective of this section is to describe a framework able to specify an interface compatible to link the EnerMan system to the production systems in particular for downstream information (control).

Due to the heterogeneity of the industrial scenarios (presented in the previous section), the interface specification of the developed EnerMan modules towards legacy system controllers is relevant and

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essential. An appropriate approach consists in considering the different devices as belonging to a group rather than to manage all the possible interfaces generated by all the instances of the device-device pair. As a result, a generic semantic representation to share structured knowledge from different perspectives and contexts is required. This representation should allow this knowledge to be exploited on the various heterogeneous systems when deploying control strategies from the EnerMan system to the industrial scenarios.

An ontology provides a unifying framework for a shared understanding between various viewpoints whatever the stakeholders' needs and their context. As a result, ontology can have the necessary depth to represent similar objects. According to the classification of Uschold and Grüninger (Uschold and Grüninger 1996), an ontology presents four levels of formalisation, of which only the formal level can support deduction mechanisms, in particular for problem solving in the systems engineering domain. Thanks to its generic representation (abstraction level), ontology is useful for the requirements definition, the automation of consistency checking and the reusability of similar concepts in multiple contexts. Considering the domain of interest, the devices will be grouped depending on their similar functionalities regarding their role in the control loop (around sensing and actuation concepts) and to define the interface constraints required to connect the inputs/outputs of the EnerMan system to the considered UC control system.

The details of such interface constraints are presented in Table 1.

Table 1 Interface specification needs

EnerMan System modules	UC Control system
Specification for downstreaming control inputs: • automated control signal transmission • API or web interface availability for human-in-the-loop control	Sensors layout, specification and rationale (used for which measurable variable ?)
	PLC specification
	SCADA specification
	Control communication network topology
	Expected integration strategy

To this end, an ontology is proposed, integrating both the multiple aspects of the EnerMan system modules (prediction, simulation, big data analytics, scheduling, etc.) and that of the production systems (PLC controllers, SCADA/EMS supervision systems, etc.).

3.2. Semantic representation (control and communication perspective), a survey

In the manufacturing context, numerous efforts have been put into developing ontologies, at different levels, for supporting information exchange and reuse, and creation of new knowledge (Giovannini et al. 2012). For example, the ONTO-PDM (Panetto, Dassisti, and Tursi 2012) ontology uses a product-centric interoperability architecture including business, engineering, and manufacturing aspects. The MASON (MAnufacturing's Semantics ONtology) proposed by (Lemaignan et al. 2006) provides three main concepts: Entity (for specifying the product), Operation (for describing all processes linked to manufacturing) and Resource (for representing concepts regarding machine-tools, tools, human resources and geographic resources), to develop architectures and tools for automatic cost estimation and to link a high level ontology with a multi-agent framework for manufacturing simulation. ExtruONT (Ramírez-Durán, Berges, and Illarramendi 2020) rather focuses on a specific manufacturing machine providing a detailed expression of production operations, systems, resources and plant layout. MaRCO (Manufacturing Resource Capability Ontology) details the capabilities of manufacturing resources (Järvenpää et al. 2019), whereas some authors propose ontologies related to manufacturing

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processes(Cao, Zanni-Merk, and Reich 2018; Lin and Harding 2007; Usman et al. 2013; Cheng et al. 2016). Some researchers focus on manufacturing services through the Manufacturing Service Description Language (MSDL), where *Manufacturing Services* are seen as Services that are provided by *Suppliers* and have some *Manufacturing Capabilities* enabled by some *Manufacturing Resources* and delivered by some *Manufacturing Processes* (Ameri, Urbanovsky, and Mcarthur 2012). Finally, these ontologies put the emphasis on production management, and not on the physical behaviour of a plant's constitutive elements.

Regarding the energy sustainability, multiple ontologies focus on energy evaluation and management in manufacturing (Cuenca, Larrinaga, and Curry, n.d.; Wicaksono et al. 2014), product lifecycle management (Borsato 2014) or manufacturing factory sustainability (Gagliardo et al. 2015; Giovannini et al. 2012).

By investigating ontologies in which manufacturing systems and their control behaviour can be accurately expressed, we find ontologies allowing for representing dynamical systems which include control (Milis, Panayiotou, and Polycarpou 2019), condition monitoring (Baader 2014; Cao, Zanni-Merk, and Reich 2018) and prognostic (Nuñez and Borsato 2018) aspects. They aim to describe and use the interactions between related sensors (Compton et al. 2012) and actuators. The P-PSO (Politecnico di Milano Production Systems) ontology integrates the physical aspect (system material definition), the technological aspect (system operational views) and the control aspect (management activities), through three main concepts: *component*, *operation,* and *controller*. Finally, these ontologies can be used to allow manufacturing systems reconfigurability (through control loop) whatever the manufacturing, providing it can be described by the features of a suitable ontology (Fumagalli et al. 2014), as ontology acts as a semantic coordination of standardised-viewed production components, to control a shop floor.

ADACOR (ADAptive holonic COntrol aRchitecture) is a domain ontology (Leitão and Restivo 2006) based on a foundational ontology called DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering)(Borgo and Masolo 2010). Foundational, or upper, ontologies are generic ontologies developed with the intention of formally describing various concepts that have similar interpretation across different domains. The SIMPM (Semantically Integrated Manufacturing Planning Model) ontology, as an upper ontology, models the fundamental constraints of manufacturing process planning (Šormaz and Sarkar 2019).

In fact, many of these manufacturing ontologies are aligned with a sensor-centric one, namely the Sensor, Observation, Sample and Actuator (SOSA) ontology (Janowicz et al. 2019) or one of its extensions such as SSN (Semantic Sensor Network) and DUL(DOLCE+DnS-Ultralite) (Haller et al. 2018). Together with the SAREF (Smart Applications REFerence) module SAREF4INMA (SAREF extension For the INdustry and Manufacturing domain) (de Roode et al. 2020), these ontologies accurately describe the concept of industrial machine, including the physical interactions between manufacturing entities, while favouring interoperability with industry standards.

Finally, a suitable ontology will be designed, consistently with the scope of this deliverable. ; ; It will be inspired by the SEMIoTICS (SEMantically enhanced IoT-enabled Intelligent Control System) scheme proposed by (Milis, Panayiotou, and Polycarpou 2019). This architecture provides a seamless way to integrate numerous new control system components and especially IoT components and to use semantic reasoning and mechanism to reconfigure feedback control systems.

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3.3. Semantic representation applied to the EnerMan control loop

Not only should this ontology represent given use cases accurately, but an important objective also to be achieved by of this ontology is to evaluate the feasibility of a solution for down streaming transfer of control recommendations and configurations, from the EnerMan system to plant equipment. In line with the SEMIOTICS ontology (Milis, Panayiotou, and Polycarpou 2019), the one presented below is essentially based on OWL-S (Martin et al. 2007) and SSN (Compton et al. 2012) ontologies (including the DUL and Systems extensions). This is a preliminary ontology focusing specifically on control aspects, a first step towards the complete iDSS ontology.

A critical question this ontology aims to address is the following: what is lacking in a use case for implementing and benefiting from an EnerMan component? Despite the fact that each EnerMan contribution should come with use case requirements, finding out missing elements is far from being straightforward. Due to dependencies between complex project contributions (i.e., multi-lateral developments, involving academic and industrial partners) and industrial realities (e.g., equipment certification, faulty sensors, etc.), integration remains challenging. This part focuses more specifically on the interactions between the EnerMan system and a use case, especially with regard to the downstream data flow, from recommendations to implementation and control.

The required pieces of equipment and software will be specified implicitly throughout the knowledge base (while an ontology describes concepts and interactions between them, knowledge, i.e., a set of ontology instances and relationships, is stored in the knowledge base). This is made possible by instantiating the ontology with both systems, the EnerMan system and the manufacturing plant within its environment. A knowledge graph is thus obtained and can be queried in order to list available hardware and software to accomplish a certain task.

Thanks to this mechanism, a manufacturing system can be controlled according to heterogeneous means: through control-compliant communication protocols or operators, either automatically or with human supervision.

Using the proposed ontology, a typical implementation scheme is presented in Figure 5, i.e., how elements should be represented and interconnected using this ontology.

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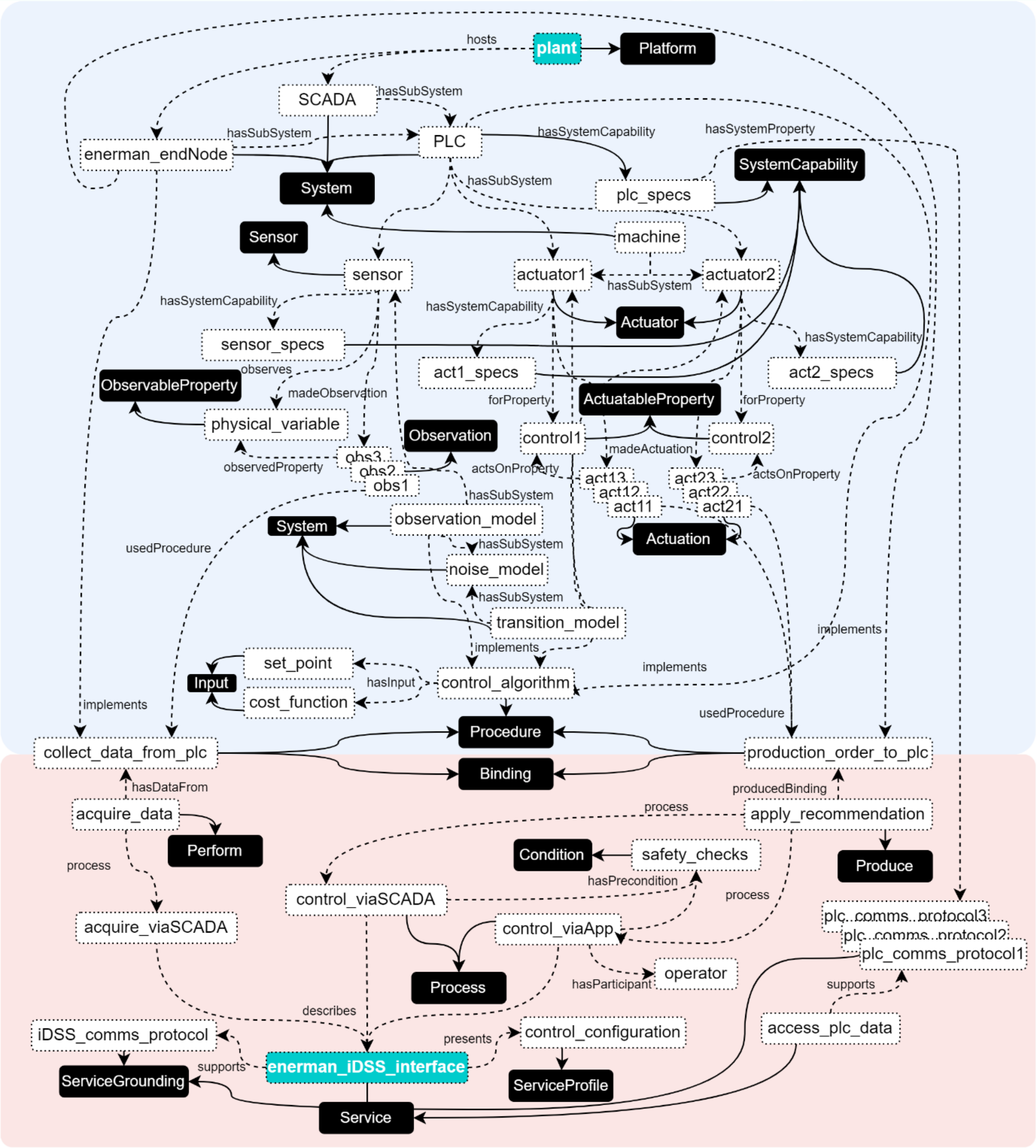

Figure 5 Ontological implementation scheme for the preliminary control loop mechanism.

The factory or plant (a `Platform`) hosts all software and hardware components. Whereas all elements of the EnerMan service are encompassed in a `Service`. Furthermore, all physical and logical aspects are described in the upper (blue) part of Figure 5 mainly using the SSN ontology. The mechanism responsible for communicating with the iDSS (EnerMan_iDSS_interface) is described using the OWL-S ontology in the lower (red) part of the diagram.

A factory's subsystems (machines, controllers, sensors, etc.) are bound together using the `hasSubSystem` object property (relationship). This mechanism allows to declare the architecture of a use case, with all its constituents.

Some control algorithms require system models. Although very accurate prediction models will be designed and made available at a higher level, simpler models should be sent and kept up to date at

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the end node's level. For this reason, transition models (i.e., system dynamics) and observation models (i.e., sensor-related observation dynamics), as well as noise models, have been added to the knowledge base in Figure 5, each model being represented as a (virtual) `System` in the SSN ontology. The models are attached to actuators and sensors in this example, but in general, a model stems from a system, i.e., models are defined as subsystems (`hasSubSystem`) of the `system` they represent. Should the modelled system have multiple subsystems, the corresponding model must account for all subsystems and integrate all possible couplings in their dynamics.

Here, the emphasis is put on the control loop mechanism, hence the EnerMan end node only collects data in the proposed ontology. Other aspects could also be represented with their dependencies though (e.g., anomaly detection module, etc.).

Communication between the iDSS and plant equipment is made physically possible using the existing PLCs' communication protocols. This is mainly described by a dedicated `Service` that `supports` PLC communication protocols (`ServiceGrounding`), and this protocol is a PLC's `systemProperty`. Typical industrial communication protocols for control signal transmission include ModBus, MQTT, 6TiSCH, ISA100.11, IEEE 802.15.4e, etc. Yet using this ontology, the orders issued by the iDSS will be directed to the EnerMan end node instead of the PLCs directly. The end node is then responsible for implementing the requested changes such as control configurations. In the ontology, a node collects data, and another sends production orders or configurations. The `Procedure` concept is therefore used; the end node `implements` both. Additionally, the two instances (corresponding to data collection and order transmission) are also the result of a `Service`. Other communication procedures are possible; alternatives include communicating directly with a SCADA system rerouting orders to the PLCs or bypassing the EnerMan end node.

The main `Service` (denoted "EnerMan_iDSS_interface") is responsible for accessing the end node and plant equipment from the iDSS, and vice versa. Safety checks and measures can also be implemented before the order goes through using the `Condition` concept, e.g., message format, data type, etc. Two communication methods are represented in Figure 5: the "control_viaSCADA" individual describes how equipment can be accessed through automated means (e.g., via control-compliant communication protocols), whereas the "control_viaApp" individual offers an alternative method for passing on production orders (e.g., via an operator applying an iDSS-originated recommendation or not). The latter can be helpful to integrate human supervision in the control loop.

3.4. Compatibility analysis between the EnerMan system and use case setups

This ontology, with the implementation scheme presented in Figure 5, allows a querying mechanism to be implemented. For instance, such a mechanism can list available control algorithms per piece of equipment, ensure a control strategy can be implemented, or validate the applicability of an EnerMan component to a given use case.

Using the Resource Description Framework (RDF), an effective querying mechanism is the Simple Protocol and RDF Query Language (SPARQL). This allows querying the knowledge base, similarly to SQL queries applied to databases.

As an illustrative example, this report assesses the theoretical feasibility of implementing a state-of-the-art class of control algorithms, namely Model Predictive Control (MPC), upon an illustrative toy use case (for visualisation purposes). There exists a myriad of possible implementations of such an algorithm. In this context, MPC acts upon a system using an estimation of its state-space model, and finds at each time step the best possible control input that minimises a cost function over a time horizon, as per the Simulink implementation (Khaled and Pattel 2018).

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In the toy knowledge base shown in Figure 5, to the question "what is missing for implementing an MPC controller?" (translated in SPARQL terms) will result in all the possible paths an order can take, from the EnerMan_iDSS_interface to the control_algorithm's parameters. Here, provided that an MPC controller also requires a time horizon (parameter, i.e., a subclass of `Input`, differentiable from other inputs), only this parameter will be missing. The paths towards this controller can be displayed though: iDSS – [control_viaSCADA or control_viaApp] – apply_recommendation – production_order_to_plc – EnerMan_endNode – PLC – [sensors] – observation_model – noise_model – [actuators] – transition_model – noise_model – control_algorithm – *missing* time_horizon (one path per `Sensor`, per `Actuator` and per service model/`Process`). This path can also be visualised on the knowledge graph, as presented in Figure 6.

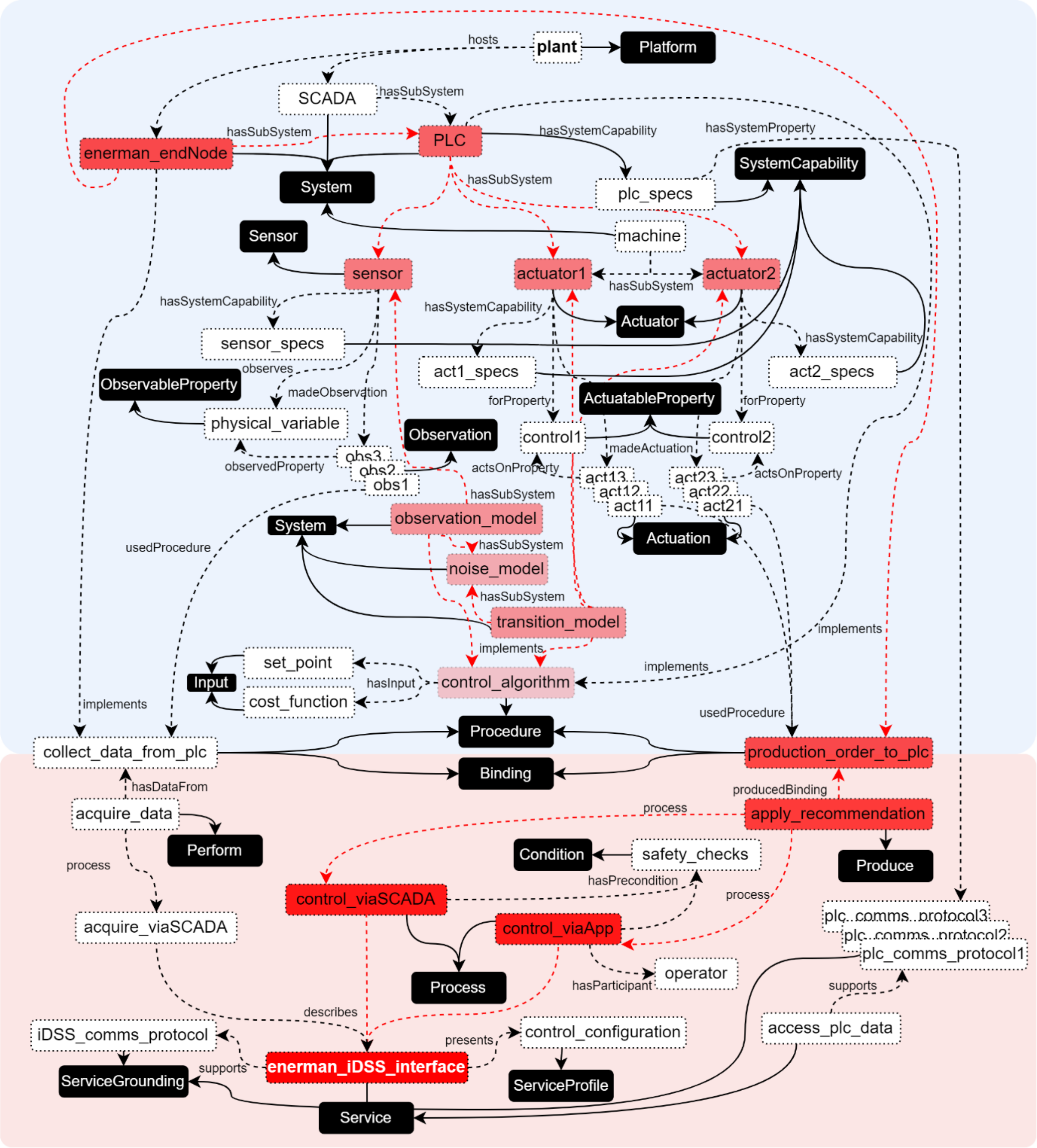

Figure 6 Concepts and predicates involved in the result of the SPARQL query, in answer to the following question: "what is missing for implementing an MPC controller?".

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4. USE CASE SIMULATOR

4.1. Academic HVAC system: implementation on MATLAB Simulink

4.1.1. *HVAC model selection, a survey*

In order to evaluate a variety of control strategies with respect to energy sustainability goals, simple yet realistic models are sought. Models currently used in control applications can be distinguished depending on their physical interpretability. “Black-box”, “grey-box” and “white-box” can thus be defined depending on the amount of physical knowledge integrated in the model and its interpretability.

On one hand, black box models, typically machine learning techniques such as multi-layer perceptrons (Kusiak, Li, and Tang 2010) or variational autoencoders (Sharif, Hammad, and Eshraghi 2021), tend to be more accurate for prediction and parameter optimisation tasks (Kusiak, Li, and Tang 2010), they lack interpretability. Interpretability is crucial for many control applications, e.g. for fault tolerant control or control synthesis in general. Grey box models, e.g., particle swarm optimisation coupled with autoregressive models (e.g., ARMA, NARX) (Afroz et al. 2022), may not be ideal either for control purposes, yet they comprehend much less parameters than black box models.

HVAC systems can include chillers and heat exchangers, cooling and heating coils, humidifiers and dehumidifiers, fans, mixing air chambers, duct and pipes. There exist a variety of technologies for each of these components, yet all except the fan rely upon thermodynamics models, e.g., chillers (Wang, Wang, and Burnett 2000; Yik and Lam 1998); cooling coils and dehumidifier (Barbosa and Mendes 2008; Homod et al. 2011; Yu, Wen, and Smith 2005); as for other components, convective models often suffice (Afram and Janabi-Sharifi 2014). Finally, complete sets of simpler models are found in (Papadopoulos 2020; Tashtoush, Molhim, and Al-Rousan 2005).

In addition to HVAC components, some disturbances can be modelled. In particular, models have been proposed in the literature with regard to occupancy (Dobbs and Hencey 2014), structural elements (doors, windows) (Homod et al. 2011) and more broadly building spaces (Massano et al. 2019).

Control applications typically relax the need for high-fidelity models. Thus the present report will focus on white box models, i.e. derived from the first principles of physics.Typical KPIs include the Coefficient Of Performance (COP) and variants targeting HVAC components (Liu et al. 2006; Magraner et al. 2010) and energy consumption. HVAC performance assessment for evaluating the benefits of new technologies or strategies often combines both aspects (Vakiloroaya et al. 2014).

4.1.2. *State-of-the-art control algorithms for HVAC applications*

Despite an extensive literature on energy-oriented HVAC control methods, there is still a growing interest for this research topic. The number of publications per year on related topics (“HVAC energy control”) has increased by 150% in 10 years, as shown in Figure 7.

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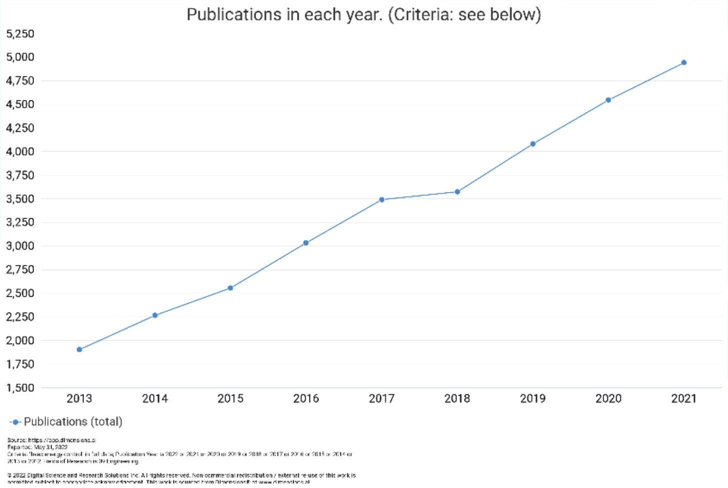

Figure 7 Number of publications per year related to "HVAC energy control". (source: https://app.dimensions.ai)

Traditional control techniques include Proportional-Integral-Derivative (PID) controllers with gain scheduling: gains can be tuned in real-time using diverse methods such as Fuzzy Logic (FL) or genetic algorithms (Afram and Janabi-Sharifi 2014). Linear Quadratic Regulators (LQR), and more generally Model Predictive Control (MPC) (Serale et al. 2018) have proved particularly effective in HVAC applications: not only target set points must be reached, with or without constraints, but MPC techniques can do so while minimising a cost function.

For dealing with multiple zones and actuators, hierarchical control strategies have also been proposed (Maasoumy, Pinto, and Sangiovanni-Vincentelli 2011), i.e., several control techniques can be applied at multiple scales (hierarchically bound together) and thus handle different aspects (e.g., occupancy at a higher level, set point tracking at the lowest level) or different time frames. Multi-zone buildings can also be handled using distributed Fault-Tolerant Control (FTC) (Mona, Jain, and Yamé 2019; Papadopoulos et al. 2018), where a sensor network can cope with potential sensor failures.

Emerging methods leverage machine learning techniques. A recent trend concerns reinforcement learning (RL) as a replacement for traditional controllers (Du et al. 2021; Esrafilian-Najafabadi and Haghighat 2022; Jiang et al. 2021), mainly to cope with uncertain occupancy and weather dynamics. Alternatively, numerous adaptive and robust control techniques have been proposed (Afram and Janabi-Sharifi 2014).

4.1.3. *Model library description*

Focusing on EnerMan's AVL use case, comprising of two testbeds, the models in (Tashtoush, Molhim, and Al-Rousan 2005) meet the appropriate tradeoff between simplicity and representativeness. These will hence serve as a basis to design the HVAC simulator. Indeed, a model is proposed for each HVAC component, albeit complex occupancy and zone models are lacking. The operations are performed in similar conditions from one test to another; occupancy can hence be disregarded or estimated as a constant source in the present simulator. Together with models for HVAC components (i.e., cooling and heating coils, humidifiers and dehumidifiers, fans, mixing boxes and ducts), the simulator includes a single four-walled room as a zone of interest, in which only a couple of terms represent disturbances (people, lights, etc.) with respect to temperature and humidity.

(1) Models for each Air Handling Unit (single component)

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A simple model for cooling and heating coils is given as (Papadopoulos 2020; Tashtoush, Molhim, and Al-Rousan 2005):

Equation 1

$$\begin{cases} C_{pi}\dfrac{\mathrm{d}T_i(t)}{\mathrm{d}t} = q_w(t)\rho_w C_{pw}\left(T_{w_{in_i}}(t) - T_{w_{out_i}}(t)\right) + (UA)_i\left(T_{amb}(t) - T_i(t)\right) + q_a(t)\rho_a C_{pa}\left(T_{a_{in}}(t) - T_i(t)\right) \\ V_i\dfrac{\partial h_i(t)}{\partial t} = q_a(t)\left(h_{a_{in}}(t) - h_i(t)\right) \end{cases}$$

where subscript i denotes a property of a specific air handling unit; C_{pi} $(J/kg/°c)$ denotes the thermal capacitance of the coil, and C_{pw}, C_{pa} $(J/kg/°c)$ denote the specific heat of water and air respectively. $(UA)_i$ is the coil's conduction heat transfer coefficient. Variables $T_{a_{in}}(t)$, $T_i(t)$ $(°c)$ refer to the air temperature at the component's inlet and outlet, with air density ρ_a (kg/m^3) and flow rate q_a(t). $T_{w_{in}}(t)$, $T_{w_{out}}(t)$ $(°c)$ correspond to the water temperature coming in and out the coil, with water density ρ_w (kg/m^3) and flow rate q_w(t). $T_{amb}(t)$ $(°c)$ denotes the ambient temperature. The volume within the AHU where air is humidified is denoted V_i (m^3); $h_{a_{in}}(t)$ and $h_i(t)$ are the relative humidity ratios (%) at the inlet and outlet respectively.

It should be noted that water refers to the liquid used to conduct heat to the air. For instance, a mixture of water and glycol is typically used to lower the temperature (i.e., lower the freezing point) of the liquid passing through a cooling coil.

Although this model hardly captures the thermodynamic cycle, this mass balance is a common approximation for such systems (Papadopoulos 2020). The air flow rate is responsible for the coupling between both equations. These components are subject to nonlinear dynamics.

This model can also approximate the behaviour observed in humidifiers and dehumidifiers, using a correction term as in (Tashtoush, Molhim, and Al-Rousan 2005).

(2) Zone model

Accurately modelling a thermal zone is tedious and complex. For the purpose of this study, a mass balance was applied to a single four-walled room. The resulting dynamics is given by (Tashtoush, Molhim, and Al-Rousan 2005):

Equation 2

$$\begin{cases} C_{pz}\dfrac{\mathrm{d}T_z(t)}{\mathrm{d}t} = q_a(t)\rho_a C_{pa}\left(T_{a_{in}}(t) - T_z(t)\right) + \sum\limits_{j\in\{wall_{1,2,3,4},roof\}} (UA)_j\left(T_j(t) - T_z(t)\right) + \dot{Q}_{ext} \\ V_z\dfrac{\partial h_z(t)}{\partial t} = q_a(t)\left(h_{a_{in}}(t) - h_z(t)\right) + \dfrac{H_{ext}(t)}{\rho_a} \end{cases}$$

where the temperature and humidity of the zone are denoted $T_z(t)$ and $h_z(t)$ respectively. At the zone's inlet, air has temperature $T_{a_{in}}(t)$ and $h_{a_{in}}(t)$, flow rate $q_a(t)$, density ρ_a and specific heat C_{pa}. $\dot{Q}_{ext}$ (W) and $H_{ext}(t)$ (kg/s) are the heat gains and the evaporation rate from external factors (people, lights, etc.). The walls and the roof all possess a temperature $T_j(t)$, as well as a heat transfer coefficient $(UA)_j$.

(3) Key Performance Indicators

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Energy consumption and power (consumption rate) are used as KPIs in this study. Given a model for the Carbon Emission Signature (CES) (Jeswiet and Kara 2008), e.g., a lookup table or a prediction model, carbon emissions can be estimated. Similarly, if a model is available, energy cost can be computed as well.

Thermohydraulic power (W) for cooling and heating coils, as well as humidifiers and dehumidifiers, is computed as:

Equation 3

$$P_{TH}(t) = q_w(t)\rho_w C_{pw}\left(T_{w_{out}}(t) - T_{w_{in}}(t)\right)$$

where hot or cold water (with density ρ_w and specific heat C_{pw}) enters an HVAC component with temperature $T_{w_{in}}(t)$ and flow rate $q_w(t)$. Output temperature is $T_{w_{out}}(t)$.

Industrial fans often consist of a three-phase asynchronous motor; electrical power is thus given as:

Equation 4

$$P_{elec}(t) = \sqrt{3}\,\cos\phi\, UI \propto \left(q_a(t)\right)^3$$

where U and I denote the root mean square (RMS) of the supplied voltage and current respectively. The power factor is denoted $\cos\phi$. In this model, in order to match the energy domains at play in the other HVAC components, this power is assumed to be proportional to the cube of the air flow rate $q_a(t)$ the fan imposes.

4.2. Application to use case AVL TB403

The HVAC simulator proposed in this report uses the above model library and is applied to the AVL use case. The simulator was implemented using MATLAB Simulink, it includes a model library, an initialisation script as well as a core model for each test case, control strategy and algorithm. As a member of the EnerMan consortium, AVL offers two vehicle testbeds as test cases for EnerMan developments, named TB402 and TB403 respectively. Only temperature and humidity regulation within the testbed is taken into account, all other aspects are deemed out of scope.

Both testbeds are fairly similar in terms of structure and components. Indeed, both consist of a couple of AHUs: the first one filters outside air arriving to the testbed and regulates its temperature and humidity; whereas the second one further humidifies and cools down the air recirculating into the chamber (TB402 also includes a fan for speed testing).

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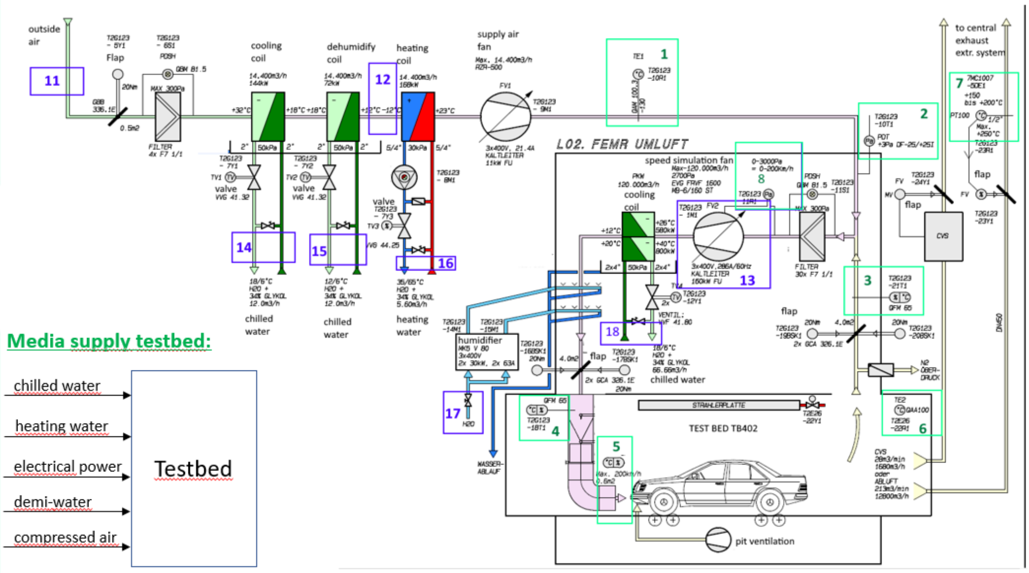

Figure 8 AVL TB402 use case, two AHUs jointly controlling temperature and humidity within a testbed chamber, and a fan controlling air speed arriving to the vehicle's front.

The simulator was designed for both use cases. Due to their similarities, all developments and results presented in the remainder of this report relate to TB403. Most remarks are still valid from a testbed to another.

TB403 is particular in that the air within the chamber must reach extreme conditions, i.e., temperatures as low as -30°c.

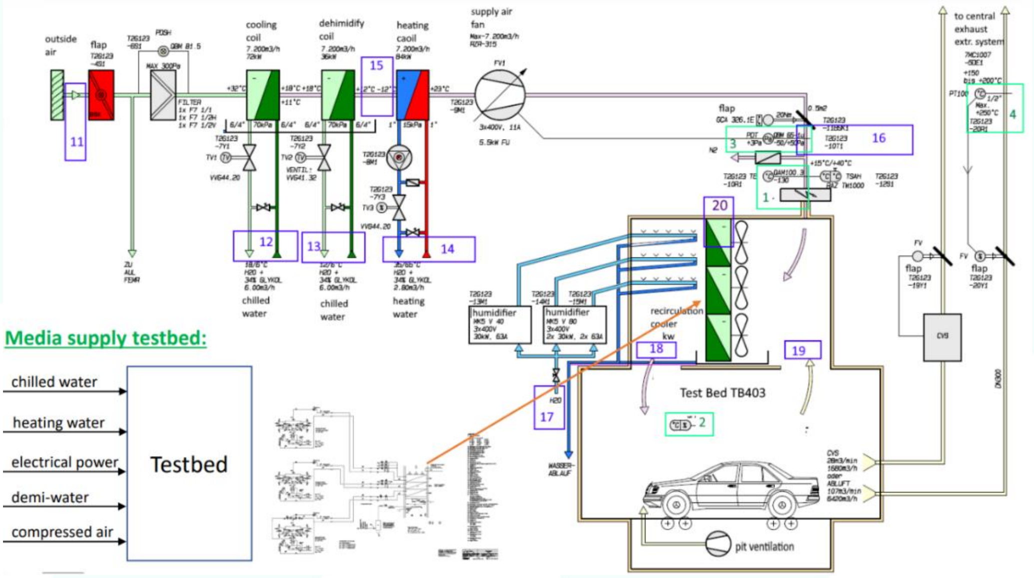

Figure 9 AVL TB403 use case, two AHUs jointly controlling temperature and humidity within a testbed chamber.

The resulting simulator, presented without control in Figure 10, consists of all actuators laid out flat, i.e., the two AHUs cannot be explicitly distinguished, yet the layout has been made similar to the actual layout in Figure 9. The blocks in pink correspond to energy meters allowing for measuring each component's energy consumption and power (the fan block directly comes with an energy meter, hence not represented in the diagram). Although in reality there exist ducts and pipes all along the circuit, all related losses have been embedded into a single *Duct* element. One such duct is placed after the first AHU, as the second one is placed at the zone's exhaust (recirculating part). The exhaust

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has not been modelled otherwise. The mixing box accounts for the properties of the air within the chamber; the air flow is imposed solely by the fan. The network distributing chilled and heated water to the components has not been modelled, as information regarding such a network is not available in reality, from a testbed's point of view. That is, a testbed has no influence on incoming water temperature; flow rate is however controlled.

The air flow rate is dictated by a single fan in TB403. Consequently, the air flow rate passing through the coil is assumed to be constant.

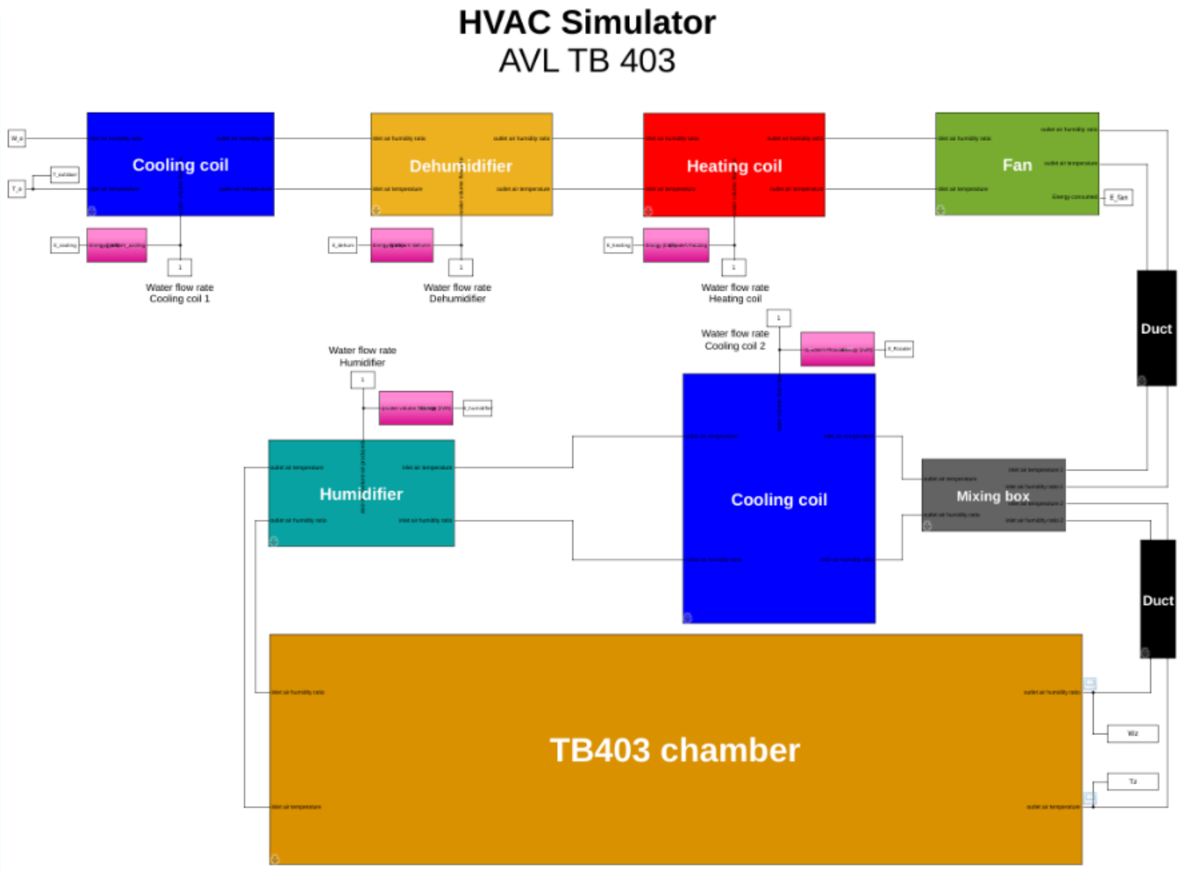

Figure 10 Simulink HVAC simulator without control.

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5. CONTROL STRATEGIES

5.1. Different control strategies: distributed, semi-distributed, centralised

In this section, control is added to the model. Three distinct control strategies are considered. In the (fully) distributed control strategy, each actuator is controlled independently using locally available sensor data. The centralised control strategy uses a single control law for all actuators, taking only relevant information as input (i.e., intermediate sensor data is not compulsory). At last, the semi-distributed control strategy corresponds to a tradeoff between distributed and centralised control strategies: an intermediate sensor can be used for controlling several actuators.

It should be noted that a single manufacturing cell is considered here; in a network of AHUs and zones, distributed control may refer to independent cells (or at least having a certain degree of autonomy).

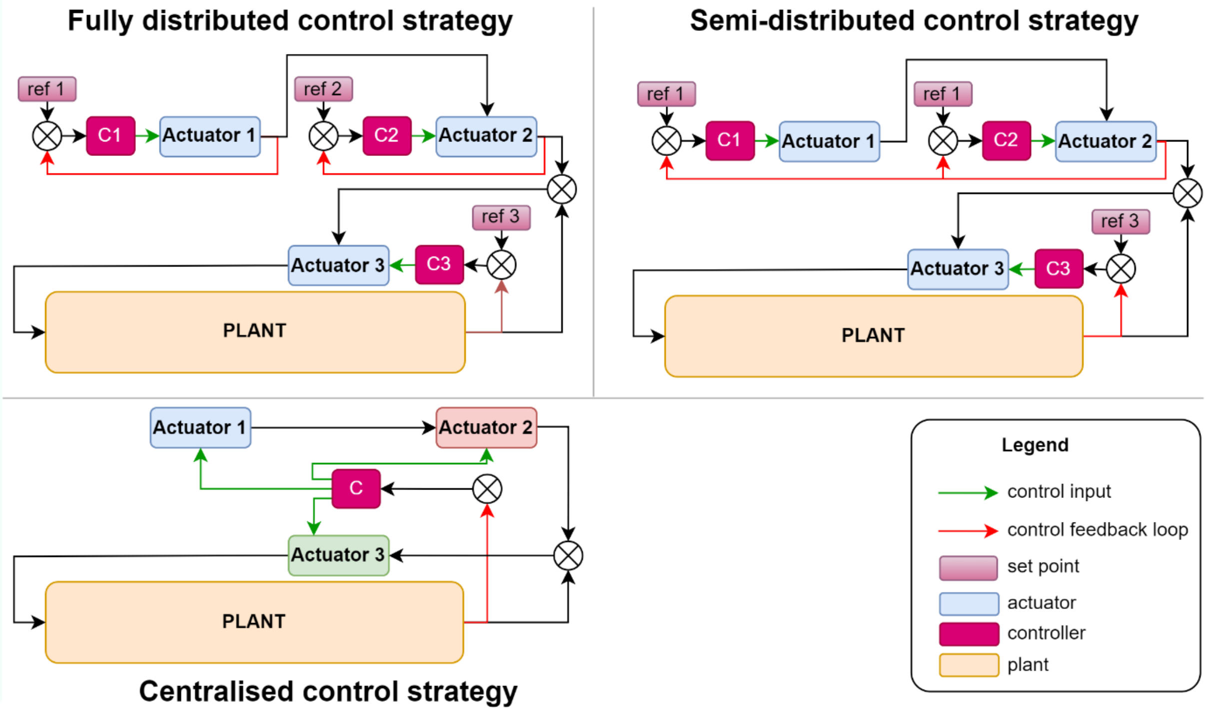

Figure 11 Three different control strategies applied to a common HVAC architecture (AHU controlling supply air, with another AHU controlling recirculated air).

As presented in Figure 11, a series structure is considered: every actuator affects the next one as a disturbance. An actuator's set point depends on the strategy, and more specifically on the location of the sensor used for controlling this actuator. Distributed control strategies obviously assume intermediate sensors to be available, i.e., placed in between air handling units.

The AVL use case (TB403 in particular) implements the semi-distributed control strategy using PID controllers at the time this report is written.

5.2. Implementation and optimisation

It should be noted that model fitting is beyond the scope of this document. The following results are more qualitative rather than quantitative, focusing on trends and presenting a methodology to assess different control strategies.

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Two control algorithms have been implemented: PID and MPC controllers. Both require a set point and aim to reduce the steady-state error with respect to this reference. PID controllers can be configured using three gains (proportional, integral and derivative gains respectively). Whereas MPC controllers also minimise a cost function over a time horizon. MPC requires a prediction model (with or without constraints), and it is parameterised by the time horizon and weights (internal to the cost function) in particular, as well as all necessary optimisation parameters. The two algorithms' hyperparameters have been optimised using MPC Designer and PID Tuner in Simulink. Unlike PID controllers, MPC controllers can handle multivariate time series. As a consequence, coupling between physical variables can be taken into account in such a control algorithm.

5.2.1. *Distributed control: Simulink models and control parameter optimisation*

The distributed control strategy applied to the HVAC simulator is presented in Figure 12. This strategy represents an extreme situation where all actuators are controlled independently. Although this strategy may appear as more expensive at first, integration is much simpler due to the lack of interactions between systems. Yet this configuration is not convenient in practice, as it requires at least one sensor per actuator, placed at potentially intrusive locations (e.g., within an AHU after each component). Furthermore, in such a configuration, intermediate set points need to be set independently. Consistency must thus be ensured by prior calculations (i.e., optimal set points must be computed) instead of being implicitely accounted for within the control algorithm.

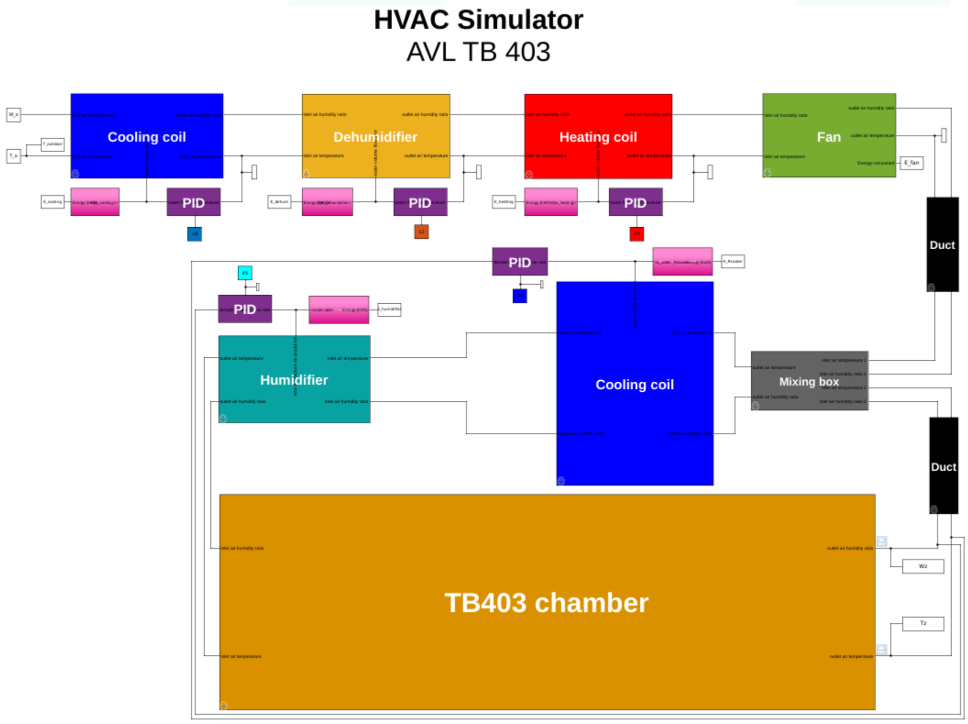

Figure 12 Fully distributed control strategy applied to the HVAC simulator

5.2.2. *Semi-distributed control: Simulink models and control parameter optimisation*

The semi-distributed control strategy applied to the HVAC simulator is presented in Figure 13. A tradeoff between ease of integration and performance is obtained using this semi-distributed configuration. Indeed, sharing sensors among several controllers and actuators relaxes the need for intermediate sensors and allows sharing the objective as well (i.e., several actuators are controlled according to the same goal, aiming to reduce the same error via proxies).

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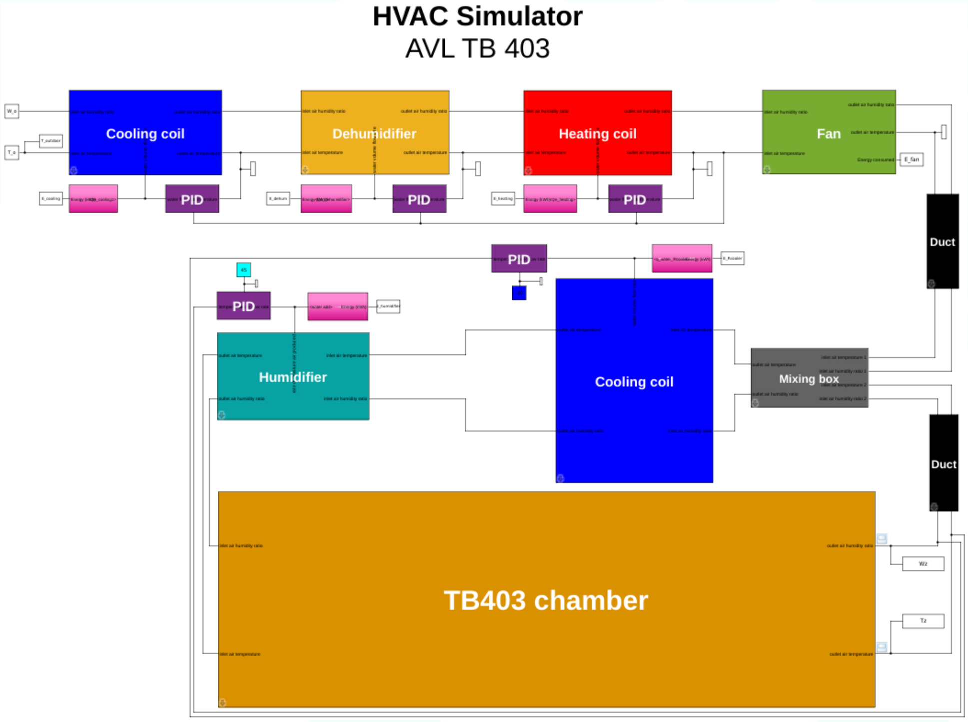

Figure 13 Semi-distributed control strategy applied to the HVAC simulator.

5.2.3. *Centralised control: Simulink models and control parameter optimisation*

The centralised control strategy applied to the HVAC simulator is presented in Figure 14. This control strategy assumes sensor data to be available at a central location (e.g., using a SCADA system), from where all actuators can be piloted.

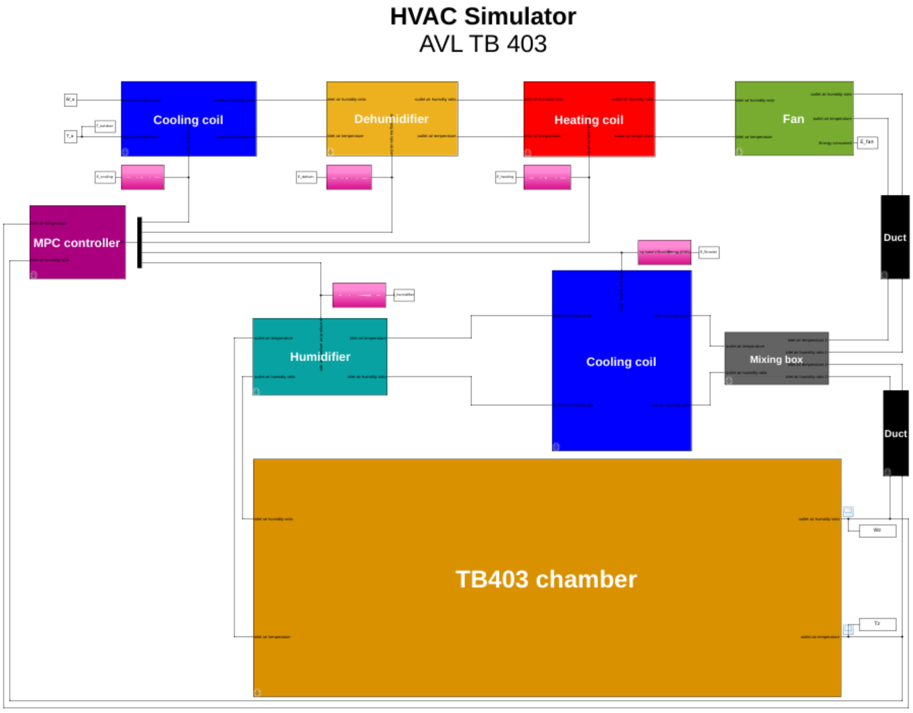

Figure 14 Centralised control strategy applied to the HVAC simulator.

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5.3. Performance analysis

5.3.1. *System (output) performance*

Using this simulator, control strategies and algorithms can be compared with one another. Many control parameters can be used to this effect. For instance, typical control performance parameters include the following: rise time, steady-state error, and overshoot. All three can be inferred from a step response and observed on the resulting time series. Although these are formally defined for systems up to the second order, they can be approximated on other systems with similar responses, such as the ones below.

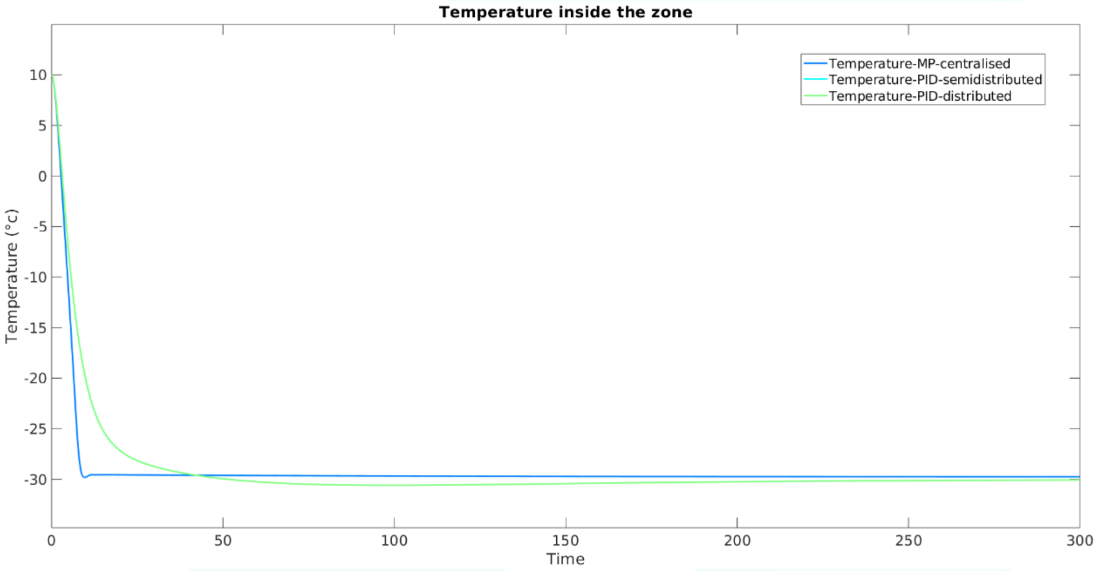

Figure 15 Temperature inside the zone, response to the centralised, semi-distributed and distributed control strategies.

The MPC controller applied to a centralised control strategy yields the best performance for temperature and humidity responses, with regard to rise time, overshoot and steady state error. The MPC controller has been parameterised for an aggressive response, and indeed, it is the most damped of all three responses. Other optimisation goals can be set.

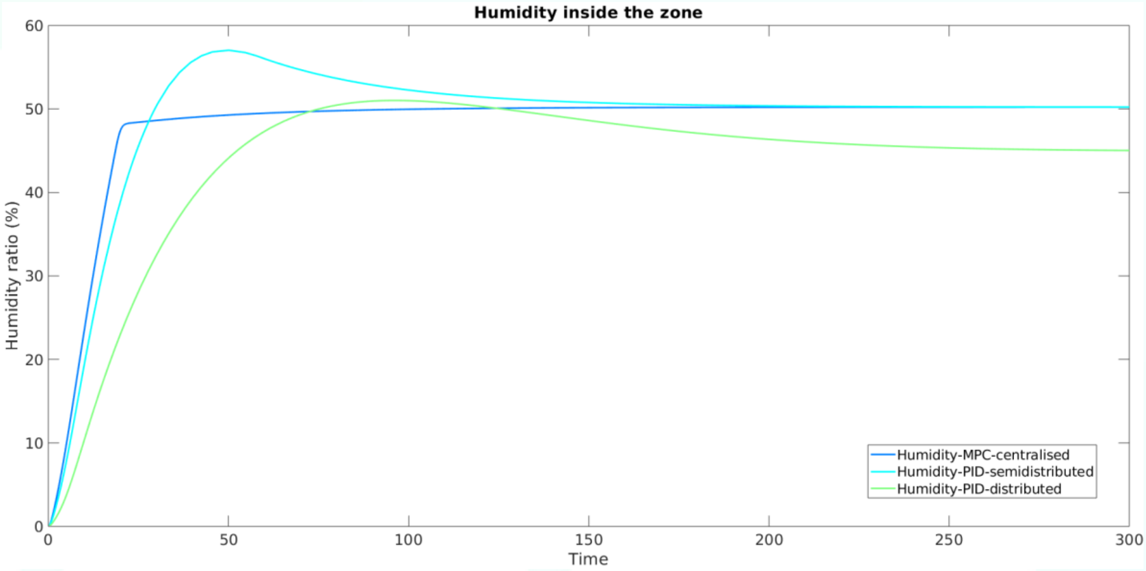

Figure 16 Humidity ratio inside the zone, response to the centralised, semi-distributed and distributed control strategies.

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5.3.2. *Energy sustainability performance*

The simulator also allows for energy sustainability performance to be assessed for each controller and control strategy. In Figure 17, Figure 18, Figure 19, the energy consumption of every actuator present in the HVAC use case is displayed (Equation 3 and Equation 4), for the three control strategies considered.

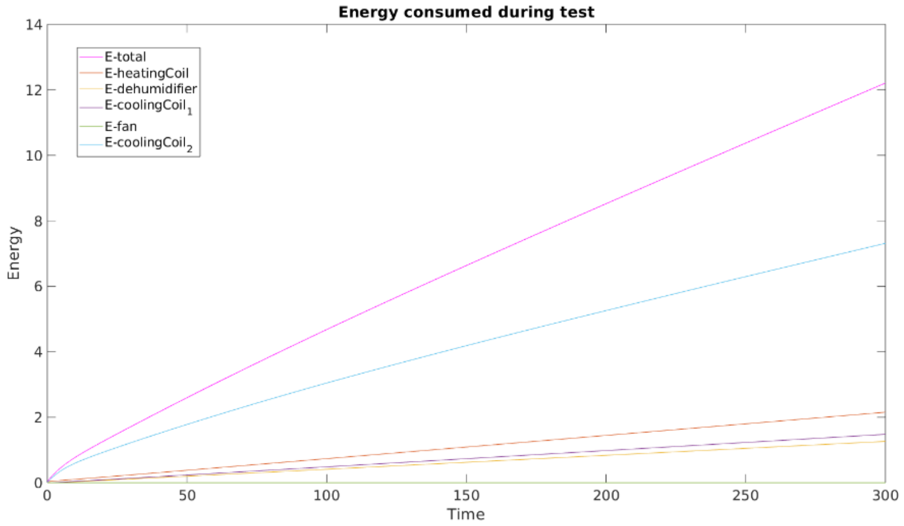

Figure 17 Energy consumption per component, response to the fully distributed control strategy.

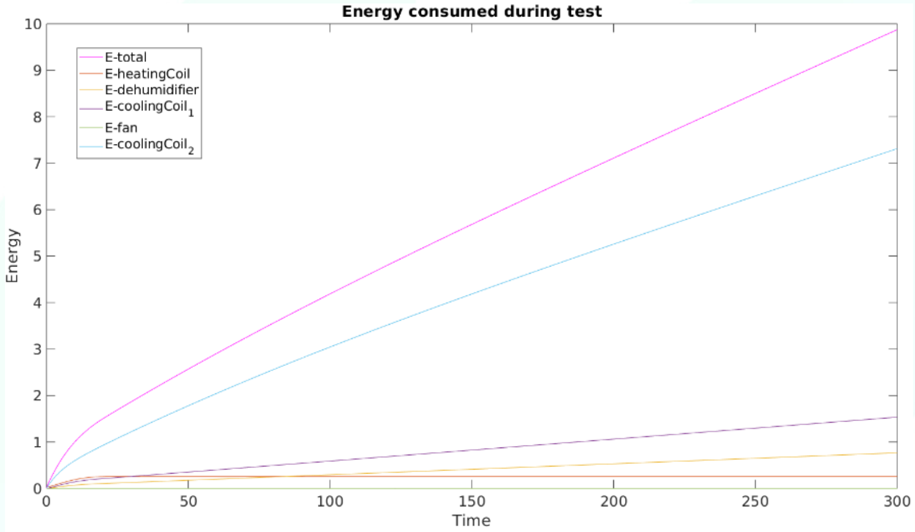

Figure 18 Energy consumption per component, response to the semi-distributed control strategy.

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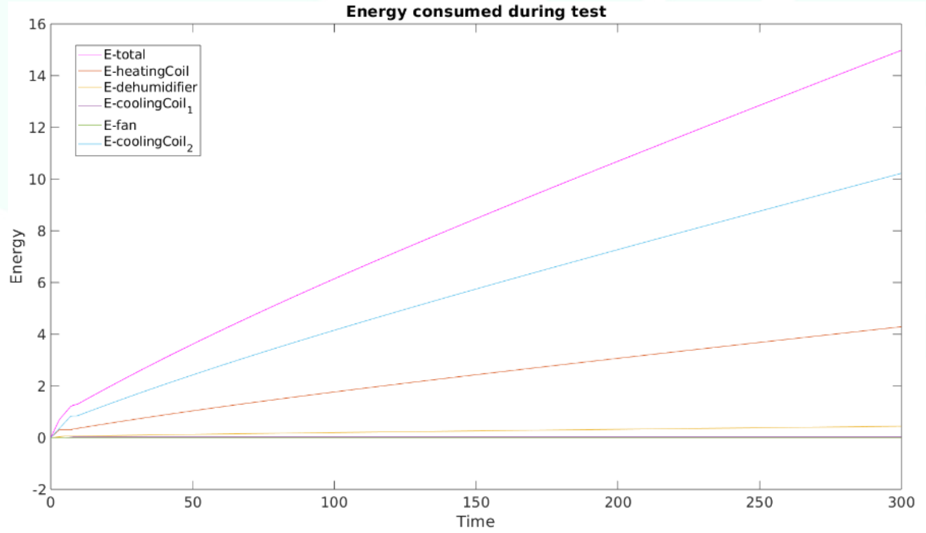

Figure 19 Energy consumption per component, response to the centralised control strategy.

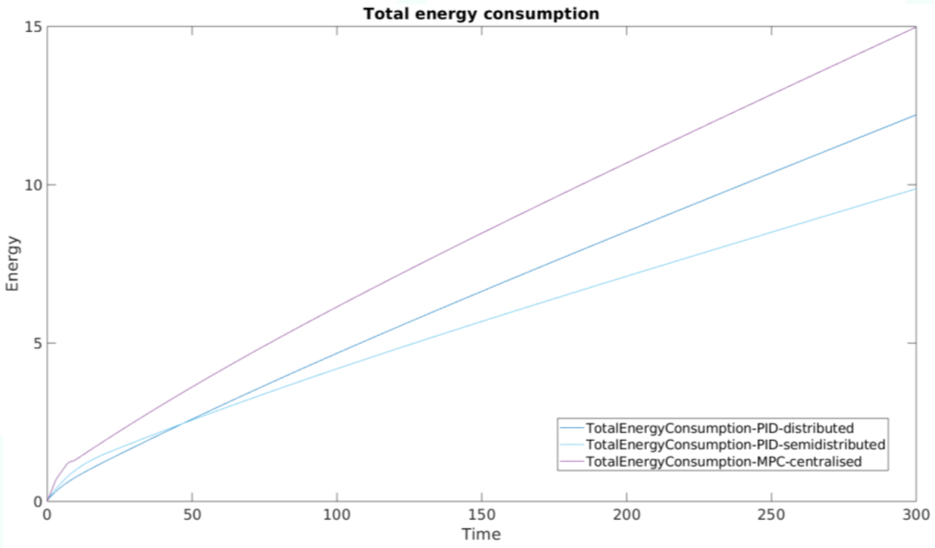

Figure 20 HVAC energy consumption, comparison between the different control strategies.

Finally, control strategies can be compared with one another according to the total energy consumption they induce while fulfilling the same goal (same set point over the same time frame), as presented in Figure 20. The controllers implemented in this study specialise in reference tracking. That is, these control algorithms aim at reducing the steady-state error, while reaching control performance indicators (mainly the response time in this case) using hyperparameter optimisation. As a result, the centralised control strategy using an MPC controller as implemented in Simulink provides the best results in terms of control performance. Better energy consumption is hence expected from such a strategy, by optimising the parameters with respect to energy consumption instead of control indicators. This trade-off between performance and energy consumption is obtained by tuning a cost function, yet none of the MPC Simulink blocks had such capability (without causing stability issues) to the best of the authors' knowledge. Alternatives exist or can be developed on other platforms or languages though, e.g., using MATLAB with the Model Predictive Control Toolbox[1] and Optimization Toolbox[2].

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[1] https://fr.mathworks.com/products/model-predictive-control.html

[2] https://fr.mathworks.com/products/optimization.html

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6. CONCLUSIONS

This deliverable contributes to the second work package of the EnerMan project in three ways: listing available equipment and practices (based on the consortium’s pilot use cases), proposing a control loop mechanism, as well as listing and proposing a methodology for control strategy assessment.

In order to help with the integration of EnerMan components into existing use cases, an analysis of the EnerMan use cases has been conducted focusing on currently implemented control mechanisms, using available information. A synthetic map of legacy pieces of equipment (PLCs, EMS, machines, etc.) and architecture (communications and plant layout) has been proposed for two use cases.

A preliminary control loop mechanism has hence been proposed and formally described using an ontology, based on existing standards regarding manufacturing and Industry 4.0 ontologies. This ontology has been developed so as to make possible its alignment with the iDSS ontology to be designed in Task 3.4 of the EnerMan project (iDSS design). Due to industrial constraints, such as equipment certification or unavailable control hardware or software, alternatives (e.g., an app enabling human supervision for some actions) could be developed under the same ontological blueprint as the automated control signal transmission.

Furthermore, control strategies and state-of-the-art control algorithms have been introduced, together with an HVAC simulator allowing their performance assessment, both regarding plant output (i.e., mainly temperature and humidity ratio in the AVL use case) and energy performance (i.e., energy consumption in this case).

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APPENDIX A: TECHNICAL QUESTIONNAIRE ON USE CASE ARCHITECTURE

T2.3 – Technical Questionnaire

I. INTRODUCTION

The following questions relate to the control and communication aspects of the use case: equipment specifications and layout; control input, objectives, and constraints. This will support the control studies in D2.4 and preliminary interface specification (T2.3, T5.1) with the EnerMan system.

Please detail your answers, regarding the layout and the data flow in particular.

NB: This questionnaire supplements the Data collection and submission guidelines. Please kindly provide harmonized data as per these guidelines.

II. QUESTIONS

1. Which KPI do you use or intend to use?

1.1. Please provide the formula (and a short description for its constitutive variables/parameters) corresponding to each KPI (energy- or production-related), as well as the expected performance (or quality criterion).

KPI	Formula	Criterion
e.g. #1: Total hydraulic energy consumption	$KPI = \sum_i q_i p_i$ q_i input flow rate (m3/s) to each machine. [**sensor #42**] $p_i$input pressure (bar) to each machine [head = 2 bar]	Minimize. Typical range: 0-100kW

2. Equipment interoperability and control strategies in place

2.1. Please kindly list down all sensors and actuators.

Actuator (with TAG)	Command type & range	Energy supply	Output type
e.g. HeatingCoil#ZULUFT	Valve position [0-10] (discrete)	Thermohydraulic (hot water)	Air Temperature Air humidity

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Sensor (with TAG)	Measurement type & range	Meter type	Supplier / reference
e.g. Temperature#1	Temperature [-20°C … +50°C]	PT100	Siemens

2.2. For each actuator, what is the current control strategy?

Actuator	Sensors	Ctrl Variable/ref	Ctrl law	Ctrl parameters
e.g. HeatingCoil#ZULUFT	Temperature#1	Temperature	PID	Kp=1, Ki=0, Kd=3

2.3. What are the specifications of the controllers in place? To which sensors and actuators are they connected? (any datasheet would be most welcome)

PLC	Model / Supplier	Connects to	using protocol	Sampling frequency
e.g. PLC# ZULUFT	Siemens SIMATIC S7	**HeatingCoil#ZULUFT** **Temperature#1**	PT100	1 command/min 1 sample/min [max. PLC frequency 6 kHz]

2.4. Is there a supervisory control and data acquisition system? Should there be more layers (e.g. multiple controller LAN, connected to local HMIs, connected to company-wide HMIs…), please detail the architecture in the following table.
Please also include the Energy Management System in place.

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SCADA	Model / Supplier	Connects to	using protocol
WinCC SCADA	SIMATIC / Siemens	**PLC# ZULUFT**	Industrial ethernet

2.5. For each SCADA / PLC, is there an API the EnerMan system could use in order to retrieve and pass on information? Any piece of information regarding interoperability and integration would be most welcome.

Equipment	API name	Using querying system	over protocol
WinCC SCADA system		CSV export	(manual)

3. Data

3.1. Please update the dataset according to the EnerMan harmonization specifications, in ANNEX. (including, within the data file, the sensor tags).

3.2. Where could we find weather forecasts to approximate external factors? (Plant precise location, local weather channel/website…)

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