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# A holonic multi-agent methodology to design sustainable intelligent manufacturing control systems

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## A B S T R A C T

The urgent need for sustainable development is imposing radical changes in the way manufacturing systems are designed and implemented. The overall sustainability in industrial activities of manufacturing companies must be achieved at the same time that they face unprecedented levels of global competition. Therefore, there is a well-known need for tools and methods that can support the design and implementation of these systems in an effective way. This paper proposes an engineering method that helps researchers to design sustainable intelligent manufacturing systems. The approach is focused on the identification of the manufacturing components and the design and integration of sustainability-oriented mechanisms in the system specification, providing specific development guide-lines and tools with built-in support for sustainable features. Besides, a set of case studies is presented in order to assess the proposed method.

### Keywords:

Sustainability  
Multi-agent systems  
Holonic control  
Manufacturing  
Design method

## 1. Introduction

The need for achieving overall sustainability in industrial activities has been identified by many governmental reports, research and industrial roadmaps, and research developments (Garetti and Taisch, 2012; Fang et al., 2011; Merkert et al., 2015). This urgent requirement has arisen due to several established and emerging causes: environmental concerns, diminishing non-renewable resources, stricter legislation and inflated energy costs, increasing consumer preference for environmentally friendly products, etc. Many research works were reported in the specialized literature proposing different approaches to tackle sustainability at different levels of the whole manufacturing system. Nevertheless, there are open problems that still remain unsolved and require urgent attention from academia and industry practitioners. One such problem is on the field of Sustainable Production and is related with the lack of approaches that can be used to transform production processes to be more sustainable. This is a complex problem since in order to achieve sustainability in production, all the components, processes and performance indicators must be taken into account

at all relevant levels (product, process, and system) (Jayal et al., 2010). Moreover, the whole life cycle of manufacturing systems must be taken into account, considering its different layers in a holistic way. Salonitis and Ball, in (Salonitis and Ball, 2013), described the new challenges that the system designer must face in order to add sustainability requirements as a new driver in manufacturing system development. They also pointed out that it is crucial and urgent for the system engineers of sustainable manufacturing systems to have tools and methods that can help to undertake this task.

Aligned with these principles, our contribution relies within the field of Intelligent Manufacturing System (IMS). Specifically the focus is on agent-based/holonic manufacturing systems (MAS/HMS) as a powerful approach for developing IMS. A MAS/HMS manufacturing system is conceived as a distributed intelligent system in which every manufacturing component, element, and/or resource is modeled and controlled by means of software “agents/holons” that can cooperate in order to solve complex problems. An agent/holon is an autonomous and flexible computational entity capable of social interaction (that is, it is able to communicate/cooperate with other agents) (Giret and Botti, 2004). MAS/HMS manufacturing control systems are known to comply with the need for reactivity and adaptability of future sustainable manufacturing systems (Giret and Trentesaux, 2015a). The cooperation among

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agents allows an equitable resource allocation (like energy allocation) that can lead to a “social welfare” (Chevalerey et al., 2006). Moreover, since MAS/HMS is based on the interaction of autonomous decisional entities (agents/holons), the integration of local and global sustainability-oriented decisional and informational intelligent mechanisms should be easier than with a centralized and monolithic approach. The research activities in the MAS/HMS field provide a large list of engineering methods tailored to deal with specific aspects for designing agent-based or holonic-based IMS (ANEMONA (Giret and Botti, 2009), ADE (Vrba et al., 2011), ROMAS (Garcia et al., 2015), DACS (Bussmann et al., 2004), ACS (Vrba, 2013), among others. Nevertheless, most of the existing approaches do not integrate specific support for designing sustainable multi-agent and holonic manufacturing control systems (Giret and Trentesaux, 2015a). One of the major challenges in developing such approaches is the lack of guidelines and tools that pay attention to sustainability issues at design phases of the IMS. In this context, this paper specifically deals with two key questions: (Q1) What features are key to integrate sustainability efficiency when designing IMS? (Taticchi et al., 2013; Taticchi et al., 2015); (Q2) How can these features be integrated using concepts from IMS engineering methods?

The above-mentioned questions motivate this work and therefore in this paper we propose an engineering method that helps researchers to design Sustainable Intelligent Manufacturing System (SIMS). This new method, named Go-Green ANEMONA, provides the methodological benefits of MAS/HMS for the identification and specification of sustainability specific features of manufacturing systems. It is the integration of a previously released Multi-agent engineering method for IMS (Giret and Botti, 2009), and the new Go-green Holon (GGH) concept (Trentesaux and Giret, 2015) that provides design patterns in order to add sustainability features into manufacturing operation control architectures. It is focused on the identification of the manufacturing holons and the design and integration of sustainability-oriented mechanisms in the system specification. Moreover, it integrates lean manufacturing principles (Miller et al., 2010) in order to develop the SIMS as an iterative sustainability-value addition process.

The work presented in this paper is an extension of the initial ideas presented in (Giret and Trentesaux, 2016; Giret and Trentesaux, 2015b). In this way, the technical details of Go-green ANEMONA are fully presented in this paper together with a detailed validation of the proposal through three different case studies.

The rest of the paper is organized as follows. Section 2 summarizes the theories and works that motivated the development of Go-Green ANEMONA. Section 3 presents the Go-Green ANEMONA method in detail. Section 4 shows three different case studies that have been used to validate the feasibility of the proposed method. Finally, Section 5 highlights the main contributions of the paper and future works.

## 2. Related works

The main objective of our work is to provide support to systems engineers that want to implement sustainable and intelligent manufacturing systems. This section explains the implications of developing systems of this kind, bearing in mind questions Q1 and Q2 introduced in Section 1. Section 2.1 presents the backgrounds on sustainable manufacturing systems and IMS in order to present the key features that must be taken into account to properly design SIMS (some insights on answering Q1 are given in this section). Section 2.2 presents a literature review on IMS technics relevant to sustainable approaches. Finally, Section 2.3 discusses the connection between these fields as a basis on which our work is motivated

and introduced, paying attention on Q2.

### 2.1. Sustainable manufacturing systems and intelligent manufacturing systems

Sustainable development was first defined by the United Nations in 1987 (UN World Commission on Environment and Development, 1987): “... development which meets the needs of current generations without compromising the ability of future generations to meet their own needs ...”.

In general, making development sustainable involves many factors such as technology and engineering, economics, environment, health and welfare of people, social desires, and government strategies, procedures and policies, and as such is a challenging and complex task.

In the field of industrial processes, restricting the adverse environmental impacts of energy consumption is the main initiatives of the nations. The economic aspect of sustainability was the main interest in the past, whereas industrial companies have recently started to address environmental sustainability. Nowadays, due to factors such as stricter legislation, industrial standards, and rising energy costs, it is not enough for the companies to adopt a minimal environmental fulfillment strategy, but also to consider sustainability as one of the main catalysts for innovation and competitiveness (Zampou et al., 2014). Moreover, industrial challenges arising from the deregulation of the electricity markets and the increasing presence of unpredictable renewable energy sources must also be taken into account in order for a company to be competitive in today's market (Merkert et al., 2015).

The US Department of Commerce (International Trade Administration, 2007) defines sustainable manufacturing as: “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound”. Notions as lean,<sup>1</sup> clean, green manufacturing (to name a few) are often used to describe strategies or philosophies that are more or less similar in the context of sustainability in manufacturing.

Sustainable manufacturing systems are very complex systems, because they typically include several sub-systems, many dynamically changing processes, objects, containing variables that are often difficult to measure and calibrate. Developing such systems is a challenging and complex task that must be supported by sound and complete engineering methodologies that can assure a set of properties of the systems and that provide specific support for the correct treatment of the sustainability requirements.

Many manufacturing paradigms promise to meet the challenges of the factories of the future (Shen et al., 2006). Two of these paradigms, Agent based Manufacturing Systems, and Holonic Manufacturing Systems have already demonstrated successful applications. Agent based Manufacturing Systems are based on Multi-Agent System (MAS) technology (Castelfranchi and Lesperance, 2003). MAS is focused on the coordination of entities, called agents, with intelligent behaviors that interact in a group of (possibly pre-existing) agents. Holonic Manufacturing System (HMS) is based on the concept of “holonic systems”, originally developed by Arthur Koestler (1990) in order to describe the sub-wholes/parts in real-life systems, and later translated to the

<sup>1</sup> The relation among lean and green manufacturing have been often discussed. Both concepts display similarities at the level of resource productivity, organizational change, and source reduction. However, during implementation of the concepts some trade-off situations might appear. For an in-depth analysis see (Johansson and Winroth, 2009).

manufacturing world for describing the autonomous manufacturing modules (holons) with distributed control. The best features of hierarchical and heterarchical organization are combined in the HMS approach (Dilts et al., 1991): the stability of hierarchy, and the dynamic flexibility of heterarchy. In a HMS, a holon can be used for transforming, transporting, storing and/or validating information and physical objects. The reference architecture for implementing holons is defined by Christensen (2003) in which there is an information processing part, in charge of the logical and intelligent computation; and often a physical processing part (optional), in charge of controlling a physical component: a machine, a tool, etc. A holon can be part of another holon.

McFarlane and Bussmann have divided the research efforts in the field of HMS into three groups (McFarlane and Bussmann, 2003): Holonic Control Architectures, Holonic Control Algorithms, and Methodologies for HMS.

## 2.2. State-of-the-art review on IMS technics for sustainable manufacturing

The review presented in this section is structured according to the type of contributions relevant to IMS technics: MAS/HMS manufacturing control architectures on the one side and MAS/HMS design methodologies on the other side.

### 2.2.1. MAS/HMS manufacturing control architectures

PROSA (Van Brussel et al., 1998) for 'Product, Resource, Order, Staff Architecture', is historically the first architecture for Holonic MAS dedicated to manufacturing systems. PROSA is more an architecture than an applied control model or a method, it proposes to structure the manufacturing control with the following holons (from 'bottom to up', i.e. from the more reactive to the more complex): 'Resources' holons, linked to physical entities of the system (like the machine-tools); 'Product' holons that owns each the knowledge that are necessary to build a product, and that ensure the processing quality; 'Order' holons, that ensure the realization of an objective (processing of the clients demands, stock management, resources repairing ...) by managing the holons 'Resource' and 'Product'; and optional 'Staff' holons, that acts like services providers, mainly to propose new plans. Initially, the 'Order' holons plan the tasks of the 'Resources' holon according to the knowledge stored in the 'Product' holons. ADACOR (ADaptive holonic Control aRchitecture) (Leitão and Restivo, 2006) proposes also the use of four kind of holons, which are the following (from the more reactive to the more deliberative): 'Operational' holons managing the system resources; 'Supervisor' holons, responsible of the tasks schedules management; 'Task' holons, that manage the use of the physical resources linked to the tasks; 'Product' holons represent the products and the knowledge to produce them, and schedule activities of 'Task' holons. Like with the PROSA architecture, process control built with ADACOR, and its extension ADACOR2 (Barbosa et al., 2015) allows both to follow an optimal task scheduling in normal situation, and to reactively adapt to events. Other architecture have been proposed with a similar approaches like ORCA (Pach et al., 2014), Zambrano-Rey's approach (Zambrano Rey et al., 2013) and PROSIS (Pujo et al., 2009). In order to implement a concrete approach for the production planning of the different orders in the system with PROSA or ADACOR it is possible to follow a centralized and/or a distributed planning and scheduling solving process (for a large review on approaches for sustainable manufacturing operation scheduling see (Giret et al., 2015) (Klemeš et al., 2012) (He et al., 2015) (Liu et al., 2014)). Nevertheless, there is a lack on concrete guidelines that can help the system engineers to integrate sustainability approaches into PROSA or ADACOR based systems.

Recently, energy started to be considered by some HMS/MAS manufacturing control models. For example, in (Pach et al., 2015) it was presented an IMS-based approach where holons (products and resources) use Potential Fields model as interaction mechanisms to dynamically control the overall energy consumption of a FMS during its real-time scheduling. This model takes the power consumption of the resources into consideration in the decision control in addition to typical indicators such as completion time. Using this model, products adapt their decisions to respect an overall energy threshold in case of variable energy supply or energy costs. A first limit of this work is that the solution follows a purely reactive approach for scheduling manufacturing operations that does not take into account events in the near future, such as short-term energy availability forecast. A second limit is that this model does not provide any tool to balance through the design phase of the holonic control system, effectiveness (production makespan) and efficiency (energy consumption). A last limit concerns the fact that this work does not consider the advantage of predictive approaches for launching (starting) the FMS with energy-aware optimized schedules that can balance between the efficiency and effectiveness of the initial environment state. Another interesting illustrative example dealing with energy comes from the work presented in (Raileanu et al., 2015) where each production resource is associated with an intelligent agent providing the interface with information systems (e.g., MES, planning systems ...). The intelligent agent provides the resource's state, the resource's total energy consumption, the resource's operations, and the resource's performances for an operation (speed, timeliness, power consumption, quality of service, etc.). This agent observes the instant energy consumption of the resource and calculates KPIs (Key Performance Indicators) such as: energy used per operation type, total consumption, etc. The global architecture of this MAS/HMS manufacturing control system enables to dynamically support changes in the physical world.

To the best of our knowledge, the concept of Go-green manufacturing Holon (GGH) proposed in (Trentesaux and Giret, 2015) is one of the first works dealing with application of holonic principles to the sustainable control of manufacturing systems. The idea is to incite researchers to develop sustainability-oriented manufacturing operations control architectures, holonic or multi-agent, and to provide a usable generic concept that is easy to appropriate, particularize and implement. GGH provides a kind of "sustainable-oriented-template" or artifact that can be used to develop manufacturing holons. Go-green ANEMONA uses GGH as a key-modeling element (the in-depth details are presented in Section 3).

### 2.2.2. MAS/HMS design methodologies

Despite the large list of works reported in the field of MAS/HMS Manufacturing control architectures, the designers of these applications are not assisted by generic design methods. Nevertheless, some methods have been proposed to develop specific MAS/HMS applications. This section describes some of these methodologies.

In (Hilarie et al., 2008) it was proposed a definition of Holonic Multiagent System based on the notion of roles, interaction and organization, that uses a dedicated method, ASPECS (Cossentino et al., 2009), and a specific MAS platform named JANUS (Gaud et al., 2008). ASPECS follows an iterative approach, from the requirements definition to the design. The ontology of the system is firstly defined; next the roles that will be played by the agents, and the exchange between them and the entities are specified. ASPECS is not particularly dedicated to manufacturing system, and the cooperation needed between the agents to solve a problem is not explicitly described. The ADELFE method (Bernon et al., 2002) is based on the notion of cooperative self-adaptation and on the

AMAS theory (Caper et al., 2003) that aims to design adaptive agents, which avoids none cooperative situations. With this approach, an agent that receives a message is cooperative if (a) it interprets the message without ambiguity (cooperation in perception), (b) it can decide an action according the message (cooperation in decision), (c) the action it will execute is profitable for the global system (cooperation in action). The ADELFE method was applied to complex multi-levelled systems like complex manufacturing systems (Clair et al., 2008). ANEMONA method (Giret and Botti, 2009) is based on PROSA type of holons, and propose a top-down approach for the analysis and specification phases, and bottom-up approach for the design phase. ANEMONA method is one of the most complete MAS methods for HMS. It is assisted by an efficient case-tool, and a last version (Giret et al., 2016) proposes to link the agents, built with the JADE platform, with services. Despite this list of MAS/HMS design methods, none of them integrates specific support for designing sustainable multi-agent and holonic manufacturing control systems. Ideas from the method proposed in (Despeisse et al., 2012) are worth to analyze and adapt to the field of MAS/HMS design methods in order to propose specific support for sustainability features intertwined with the potential of IMS. The conceptual model of Despeisse et al. focuses on material, energy and waste flows to better understand the interactions between manufacturing operations, supporting facilities and surrounding buildings. The work is a base on which it is possible to build quantitative modeling tools to seek integrated solutions for lower resource input, higher resource productivity, fewer wastes and emissions, and lower operating cost within the boundary of a factory unit. This conceptual model is complemented with guidelines for manufacturers (Despeisse et al., 2013) to undertake the sustainability journey by guiding them through the steps of factory modeling, resource flow analysis and improvement opportunities identification. Nevertheless, in the proposed approach there is a lack of concrete activities and artifacts to help the system engineer to develop a SIMS.

### 2.3. Discussion on the state-of-the-art

The body of sustainable manufacturing literature is growing but tends to focus on the efficiency of technology or individual processes rather than overall manufacturing system efficiency. Moreover, when examining tools and techniques, there is little to support sustainable manufacturing concepts using a systems view of the factory (Giret and Trentesaux, 2015a). Architectures and methods are proposed to design MAS or HMS to control Manufacturing Systems (with some aspects relevant to energy), taking into consideration the need for adaptability and reactivity that accompanies the sustainability principles, as well as the evolution of future industrialists' need. Even if energy is now being studied as a first driver for efficiency management, exception of the concept of GGH, none of these known approaches explicitly considers sustainability aspects as a fundamental basis. Obviously, some of them could be extended or adapted (e.g., PROSA is general enough for that purpose, it may embed GGH for example or mirror sustainability-oriented mechanisms), but no work has been done in that direction. From our point of view, the main issue comes from the lack, at early development stages, of proper considerations to sustainability issues. This notion cannot be treated like another 'classical' constraint to manage by the agent in their planning phase. Sustainability in manufacturing systems, like other notions such as distribution, cooperation, emergent behavior, etc. has to be taken into account during every development step of the IMS. This constitutes the starting point of our work and the point that led us to develop the Go-Green ANEMONA development framework. Our objective is to support the design of systems that achieve efficiency,

productivity and sustainability goals. To do so, in Go-Green ANEMONA sustainability is treated as a "first-class-citizen" borrowing ideas from lean manufacturing. Lean is based on the Toyota Production System (TPS) (Jeffrey, K. Liker, 2004; Miller et al., 2010). Recent literature shows that lean techniques can serve as a catalyst for sustainability, meaning it facilitates a company's transformation towards green (Dües et al., 2013) (Bergmiller and McWright, 2009). Despite the importance of the synergistic relationship of lean and green practices, there are areas where the two paradigms' objectives can be opposite (Johansson and Winroth, 2009). Nevertheless, we believe that MAS/HMS approaches can be used to balance productivity, efficiency and sustainability during the design and implementation of manufacturing systems depending on the company objectives. Go-Green ANEMONA supports this claim by means of:

- Specific guidelines based on lean and sustainable manufacturing that can help the system designer to figure out: the sustainability parameters that are key to the manufacturing system; the way in which these parameters must be taken into account by the components of the SIMS; the situations in which these parameters must be used for achieving sustainability efficiency in the whole system; the set of approaches that can be used to compute a sustainable solution for the different tasks and processes of the manufacturing system.
- "Green" templates and/or artifacts that can provide optimized solutions at different levels such as: enterprise resource planning, production control, manufacturing operations scheduling, etc.

The above-mentioned aspects, which are related to Q1 and Q2, are the main focus of this paper.

### 3. Go-green ANEMONA

In this section we present our answer to Q2, which is a complete method for developing Sustainable Intelligent Manufacturing Systems. Go-green ANEMONA provides full support for system engineers that are seeking to have manufacturing specific guidelines and sustainability specific analysis/design activities and constructs for developing SIMS operations architectures.

Go-green ANEMONA is a complete software engineering approach for Sustainable Intelligent Manufacturing Systems based on multi-agent and holonic principles. It is based on the three pillars of every complete software engineering methodology: (1) a metamodel-based notation that details the elements used to model the system and their connections; (2) a specific process that specifies a sequence of actions and guidelines that support the design and implementation of the system; (3) a set of development tools.

Go-green ANEMONA is an extension of the method ANEMONA (Giret and Botti, 2009). Go-green ANEMONA extends ANEMONA in order to offer full support for SIMS. Go-green ANEMONA includes a new set of guidelines and integrates into its metamodel the concept of Go-Green Holons (GGH) (Trentesaux and Giret, 2015).

The rest of this section is organized as follows: Section 3.1 shows the Go-Green ANEMONA metamodel; Section 3.2 describes the software development process of the Go-green ANEMONA methodology; Section 3.3 introduces the Go-green ANEMONA development tools.

#### 3.1. Metamodel

The metamodel of Go-green ANEMONA is an extension of ANEMONA metamodel (Giret and Botti, 2009). It includes all the conceptual elements for modeling the SIMS in terms of holons,

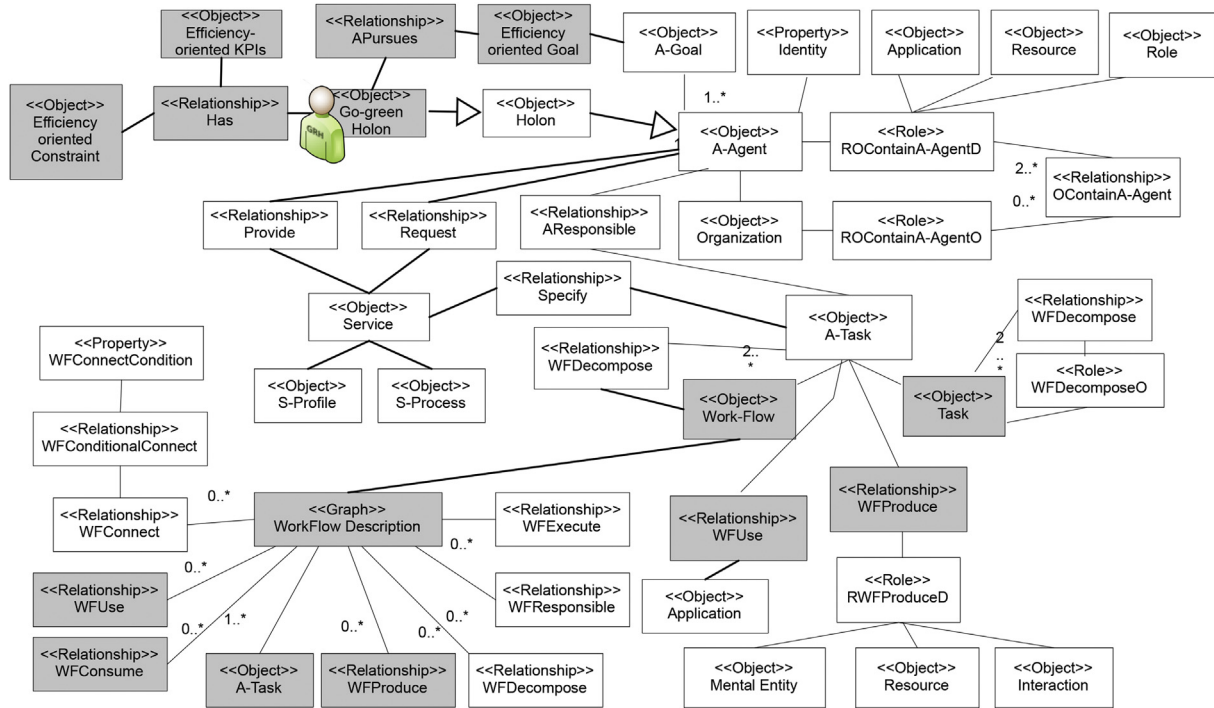


Fig. 1. Fragment of the metamodel of Go-green ANEMONA.

their static and dynamic features, organizational relationships and interaction and communication protocols. Moreover, it also includes specific artifacts and relationships that are useful for defining and embedding intelligent behaviors in order to optimize sustainability in manufacturing operations. Fig. 1 depicts a fragment of the Go-green ANEMONA metamodel in which the main modeling elements are depicted. It is interesting to remark that we use Abstract Agent and Holon as similar notions (Giret and Botti, 2004). Among the main new elements (highlighted in grey in Fig. 1) of Go-green ANEMONA metamodel the key ones are: Go-green Holons, the efficiency oriented KPIs that can be associated to these holons, and the efficiency-oriented objectives and constraints that can be related to holons, tasks, and interactions.

The Go-green ANEMONA metamodel extends the ANEMONA metamodel adding the sustainable specific elements. Moreover, some original elements from ANEMONA are extended in order to correctly deal with the sustainability features. The complete set of modeling elements to specify Tasks and WorkFlows (see Fig. 1) was extended in order to include key variables for the correct treatment of sustainable dependent values. For example in the Task and WorkFlow description the following features were added and/or extended: time for execution, hard or soft sustainable constraint variable, the WFUse, WFConsume and WFProduce relationships (among Tasks, for specifying the inputs used and/or consumed by the Tasks and the output produced by the Tasks) that relate sustainable variables (Giret et al., 2015) with the execution of Tasks. Apart from these elements, the Efficiency Oriented Goal specification was thoroughly extended in order to allow a complete specification of the different and complex combination of multi-objective sustainable goals (see (Giret et al., 2015) for an in-depth discussion on the matter). In this way the Go-green ANEMONA metamodel improves the treatment of sustainable features from the conception of the system aiding to build complete and correct sustainable models. To the best of the authors' knowledge Go-green ANEMONA is the first software engineering method that provides specific modeling elements for specifying green features. Moreover,

Go-green ANEMONA is equipped with specific software development process and guidelines for supporting the system engineer to complete the sustainable models. In the following these features are described and illustrated with some examples.

Another main modeling construct in Go-green ANEMONA that enforces sustainability in SIMS is the Go-green manufacturing Holon (Trentesaux and Giret, 2015). It is a holon that considers efficiency-oriented mechanisms (optimizing sustainability means), in addition to classical effectiveness-oriented mechanisms, to make a decision and/or execute an operation. Go-green manufacturing holons may apply different solving approaches: a balanced compromise (between effectiveness and efficiency), a lexicographical-oriented decision making process (e.g., optimize first effectiveness, then efficiency in an opportunistic way) or a constrained problem (e.g., optimize efficiency under effectiveness constraints). Multi-criteria analysis, simulation and operations research approaches can be useful in this context. Fig. 2 shows an example of a Go-green (manufacturing) resource Holon that integrates capabilities for dealing with sustainability efficiency performance in a resource. In this way when the system engineer requires designing a given manufacturing resource for tackling for example energy-efficiency in its operations, he/she can use the Go-green resource Holon that is a pre-built artifact with built-in functionalities that can be parameterized and/or fine-tuned in order to design the concrete resource with its concrete energy-efficiency parameters. In order to better understand the way a GGH operates let's consider a case study in which we have a Go-green Resource Holon that integrates predictive and reactive scheduling capabilities for balancing makespan and energy consumption. The complete case study is described in Section 4.3. Following the outline provided in Fig. 2, the effectiveness-oriented objectives and constraints for this case are: minimize the makespan, subject to maintaining the makespan below a threshold; whereas, the efficiency-oriented objectives is to minimize the energy consumption of the resource, subject to maintaining overall energy consumption below a threshold. The input data are: the

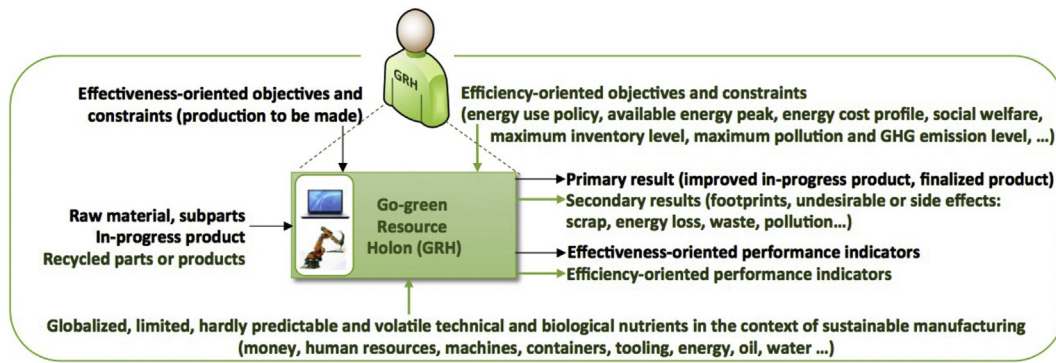


Fig. 2. A Go-green Resource Holon.

resource energy threshold, the overall system energy threshold, the list of tasks, the list of energy consumption per task, the current status of the resource and the list of scheduled tasks. The capabilities of the Go-green Resource Holon are implemented by means of four main functions: (i) an offline bi-objective optimization function to obtain an energy-aware schedule by minimizing, in a weighted sum approach, the scheduling effectiveness (makespan) and energy consumption; (ii) a resource production monitoring function that keeps track of the correct execution of the resource scheduled tasks; (iii) an online monitoring and optimization function for assuring the compliance of the energy being consumed with respect to the overall threshold for energy consumption of the system, and; (iv) a communication function capable of receiving and sending information to the outside (other holons or resource physical components/parts). A Go-green Resource Holon with the above description is instantiated for every resource in the manufacturing system and runs independently (with its own execution thread). The life cycle of every such holon is as follows. Function (i) is executed before the production task is scheduled in the resource, while functions (ii) and (iii) are executed concurrently when the resource is running a production planning. On the other hand function (iv) is continuously running in order to interact with other holons and with the physical environment. In this way the combination of the different functions and the communication services facilitated by function (iv) allow a distributed intelligent system implementation.

Modeling a complex manufacturing system in a clear and easy-to-understand way can be challenging. Therefore, in Go-green ANEMONA, the SIMS is specified, by a set of different views of the system. Each view refers to specific features of the system and provides different levels of abstractions. There are five views, or models: (1) The *agent model* that represents the functionality of each holon, its responsibilities and capabilities. (2) The *organization model* that represents how system components (holons, roles, resources, and applications) are grouped together. (3) The *interaction model* that represents and details the exchange of information or requests between holons. (4) The *environment model* that represents how the holon interacts with other non-autonomous entities. (5) The *task/goal model* that describes the relationships among goals and tasks, goal structures, and task structures.

### 3.2. Software development process<sup>2</sup>

Go-green ANEMONA software development process guides

<sup>2</sup> In Software Engineering (Sommerville, 2010) the software development process is a set of phases (or stages) containing activities with the intent of better planning and management of the software development work.

system engineers during the analysis, design, implementation, setup and configuration of a SIMS. The process is divided in different phases (or stages) that detail what should be done and which guidelines and support is offered by the methodology. The development process enforces system engineers to explicit and to think about their main design choices of the sustainable parameters taken into account in the SIMS.

Go-green ANEMONA defines a mixed top-down and bottom-up development process, and provides specific guidelines to help the system designer in identifying and implementing holons. Fig. 3 shows the development process of Go-green ANEMONA. In this figure it can be noticed that the process is an iterative and recursive sequence of specific activities. Every step in the process is assisted with a set of specific guidelines tailored for concrete aspects, such as holonic identification and specification, sustainability features, value addition, etc. At the same time, at each step during analysis, design, implementation, deployment and maintenance it is provided the specific Go-green Holon artifact that the system engineer can instantiate in order to design and implement sustainability problem solving methods. Each phase of the development process is detailed in the following subsections by: (1) the goal of the phase; (2) a workflow that shows the steps in which the phase is decomposed; (3) the description of each step showing its “products” and the guidelines that are offered to help the system engineer. Since Go-green ANEMONA is an extension of ANEMONA only the new guidelines are specified. The complete detail of ANEMONA can be found in (Botti and Giret, 2008).

#### 3.2.1. Go-green ANEMONA analysis phase

The main goal of the analysis phase is to identify the constituent holons focusing on the optimization criteria and system requirements and to provide an initial holon specification that fulfills the system description. In this phase the system requirements and the domain definition are analyzed and modeled using the different views of the Go-green ANEMONA metamodel. Moreover, the five main principles of lean manufacturing<sup>3</sup> are used to build and refine the models of the system adding value to them. These principles are applied by means of the Sustainability Guidelines presented in Table 1. This specific set of guidelines provides special support for

<sup>3</sup> The five main principles of lean manufacturing (Jeffrey, K. Liker, 2004; Miller et al., 2010): (1) Specify Value: the whole manufacturing process should be guided by the customer's demands; (2) Identify and map the value stream: identify which processes increase the value of the product (from the client perspective); (3) Create flow by eliminating waste: eliminate all the not necessary processes and reduce wastes; (4) Respond to customer pull: the systems should be able to produce just what the consumer wants when the consumers want it; (5) Pursue perfection: continuously reorganize the processes in order to decrease waste and increase productivity.

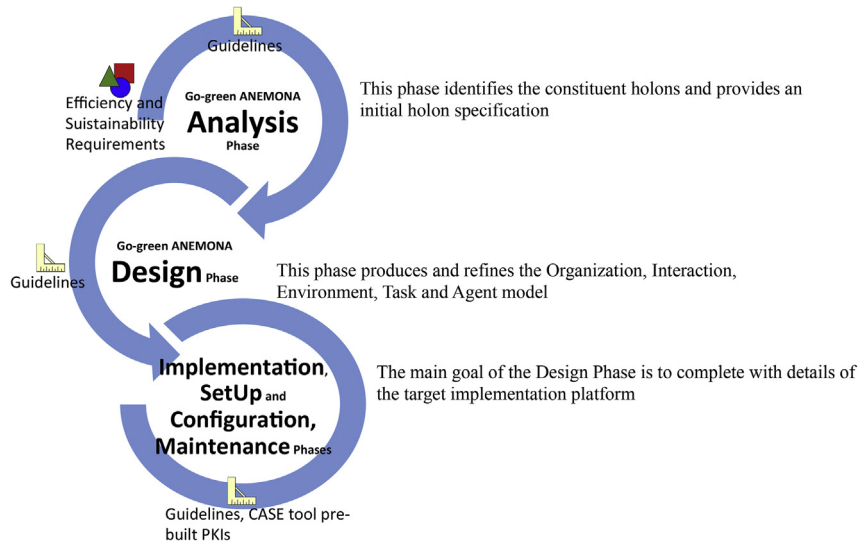


Fig. 3. Go-green ANEMONA process.

**Table 1**  
Sustainability guidelines for the analysis phase.

Sustainability guidelines for the analysis phase
1. In cooperation with the domain experts, specify the desired target values taking into account efficiency, productivity and sustainability objectives. This guideline implements principle 1 of lean manufacturing: Specify Value.
2. Revise Use-Cases to identify the value stream and eliminate all the not necessary processes. This guideline implements principles 2 and 3 of lean manufacturing: Identify and map the value stream and Create flow by eliminating waste.
3. Verify that the production responds to customer pull. This guideline implements principle 4 of lean manufacturing: the systems should be able to produce just what the consumer wants when the consumers want it.
4. From the System Requirements select the Use-Cases that includes or affects manufacturing processes and/or operations related with sustainability means (i.e. energy, CO2, pollutants, waste, scraps, etc.).
5. For every selected Use-Case add a Go-green Holon to the cooperation scenario that will be in charge of the execution of the process/operation subject to sustainability means.
6. In every cooperation scenario include a sequence message that goes to the Go-green Holon in order to calculate the efficiency-oriented KPIs.
7. Specify the efficiency-oriented objectives and constraints that every Go-green Holon must achieve.
8. Build the Consumption/Emission model for every resource/process subject to sustainability means.
9. Revise every scenario identifying the conflicts between sustainable and efficiency variables.

finding out which sustainable features will be key during the system development and for treating them as “high priority requirements” from the early system development stages. Moreover, thanks to this set of guidelines the engineer might identify new features in the system related with sustainability requirements (i.e. interaction with external elements in order to monitor sustainable values, to report sustainable input and output means to third parties, etc.)

As shown in Fig. 4, this phase is an iterative process in which the iteration is devoted to find out the constituent holons that will define the SIMS. An iterative approach for the analysis phase helps to reduce the complexity of the studied manufacturing systems since complex and large-scale problems can be analyzed using different abstraction levels, thanks to the recursivity feature of holons. The analysis phase of Go-green ANEMONA follows an iterative approach. The goal of an iteration is to find out a holonic structure (i.e. a holarchy, a set of cooperative holons) that defines a given abstraction layer. This approach reduces the time invested in the analysis of complex and large-scale problems. Moreover, it rapidly configures the starting point and the requirement specification of the different concurrent and collaborative analysis processes. Each iteration of the analysis phase identifies and specifies holarchies of different levels of recursion (holons made up of holons). The first iteration identifies an initial holarchy, which is made up of holons that cooperate to fulfill the global system

requirements. The second iteration decomposes the holons of the first level into simpler sub-holons reducing in this way the complexity of the analysis phase. At the end of each iteration, the system engineer must analyze each holon in order to figure out the advantages of decomposing it into a new holarchy or not. This process is repeated until every holon is completely defined and the system engineer decides to stop the decomposition process. Following is the detailed description of an iteration of the analysis phase that is composed of 4 steps:

#### Step 1: Determine Use Cases

Using the HMS Use Case guidelines of ANEMONA (Botti and Giret, 2008) and guideline 1 of the Sustainability Guidelines for the Analysis Phase (Table 1) the Use Cases that compose the manufacturing system are identified.

#### Step 2: Specify Use Case Realization

The Use Cases of the previous step are analyzed. The goal of this step is to add value to the SIMS applying the principles of lean manufacturing: Identify and map the value stream, Create flow by eliminating waste, and Respond to customer pull. This is done in the activities Identify Holons and Specify Environment Relations. The Sustainability Guidelines 2 to 5 of Table 1 help to associate to



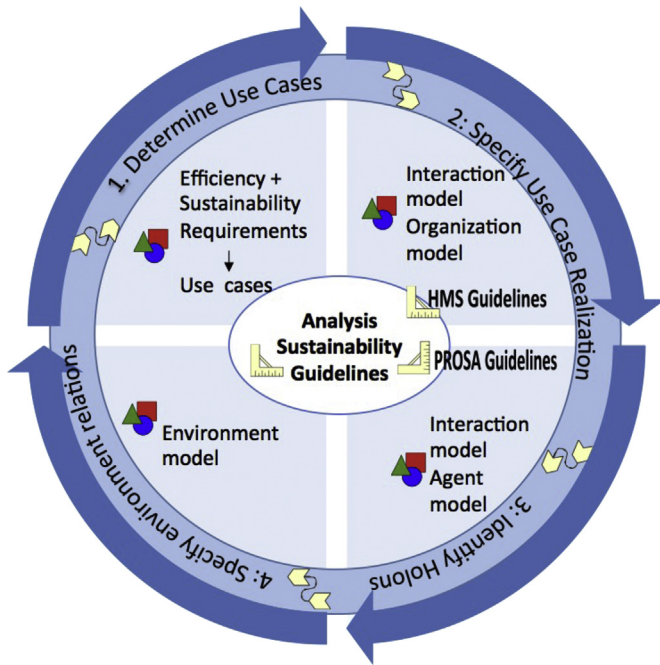


Fig. 4. Analysis phase of Go-green ANEMONA.

every Use Case a supplier of its functionality: an agent/holon. These guidelines also help to model the interaction and relationships among the Use Cases by building Interaction Models and Organization Models.

#### Step 3: Identify Holons

The system engineer works with: the models generated in the previous step, the system Requirements, the PROSA Guidelines (Giret and Botti, 2009) and the Sustainability Guidelines to identify new holons and to specify them by means of Agent Models. In this step special attention is paid to the identification of Go-green Holons.

The PROSA Guidelines, based on PROSA types of holons (Van Brussel et al., 1998), help the system engineer to identify holons and refine both the Organization model and the Interaction model by adding new or modified relations and interactions among holons in the cooperation domains. On the other hand, the Sustainability Guidelines 6 to 9 of Table 1 help to complete the definition of the sustainability features and the Go-green Holons. The Interaction models and the Agent models are completed with the sustainability related features identified in this step.

#### Step 4: Specify environment relations

The Environment Model is built in this step to represent non-autonomous domain entities with which the holons have to work. Special attention must be paid in order to reflect in this model any sustainable related inputs and/or outputs that should be required to communicate to the non-autonomous entities (examples could be: pollutant, power consumption, CO2 emission and other type of sensors).

When the five models are specified following the analysis steps described above, the software engineer has to decide if it is necessary to apply new analysis iterations. To this end, he/she has to analyze every holon in the current iteration in order to figure out whether it is convenient to decompose some of them or not. The

requirement specification for the next iteration is defined by the five models from the previous iteration that define the given holon. When the system engineer decides to stop the decomposition process (i.e. all the holons are “atomic”) he/she can proceed to the following phase in the development process (Go-green ANEMONA Design phase).

#### 3.2.2. Go-green ANEMONA design phase

The main goal of the Design Phase is to specify the System Architecture. This phase is divided into two steps (Fig. 5): Refine Holon and Build System Architecture. Moreover the set of Sustainability Guidelines of the Design Phase (Table 2) provides specific support for the system engineers in order to find out the best way to implement the computational approaches for solving the sustainable related problems in every Go-green Holon. At the same time enforcing the system engineers to perform a thoroughly verification of the completeness of the specified data and the method by which the targeted KPIs will be achieved and monitored.

#### Step 1: Refine Holon

The aim of this step is to complete the models generated in the analysis phase specifying all the parameters and constraints that might still remain uncompleted from previous phase. The system engineer must start with the “atomic” holons of the previous phase in order to complete their definitions. The Agent Model must be revised to design the life cycle of the holons, a finite state machine in which all the possible states/behaviours of the holon, during the system execution, are specified together with their transitions. In this particular step the Sustainability Guideline for the Design Phase number 1 (see Table 2) must be used in order to complete the design of the optimization functions for the sustainability means considered in the system (Giret et al., 2015). The Task/Goal Model must be analyzed to guarantee that each holon goal has a corresponding task that can fulfill it. Moreover, every modeled task must be completed with pre and post conditions of its execution. Finally, the Environment Model must be completed in order to add the resource attributes and the holon’s perceptions in terms of application events.

The system engineer must move up to the nearest abstraction

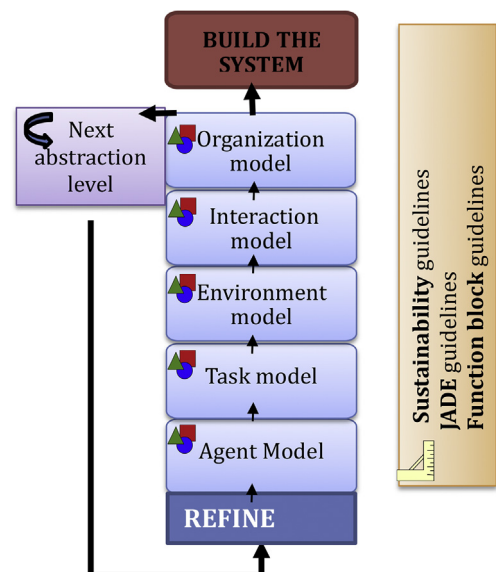


Fig. 5. Design phase of Go-green ANEMONA.

**Table 2**  
Sustainability guidelines of the design phase.

Sustainability guidelines of the design phase
1. Build and/or select a method that will be used by the Go-green Holon in order to find out the optimized sustainability solution for the given problem taking into account the efficiency-oriented objectives and constraints (see (Giret et al., 2015) for a decision flow diagram to select the best solving approach for different sustainability requirements). When there is an identified conflict between sustainable and efficiency variables a weighted formula should be created in order to decide the best solution.
2. Specify the complete list of parameters and message passing required for gathering all the data required to execute the functionalities of the Go-green Holon.
3. Verify the previously identified KPIs for the outputs.

level in the holarchy structure, from the Analysis Models, (i.e. to the cooperation domain in which the given holon interacts), when every atomic holon is completely specified. All the dependencies among the holarchies are refined in the Organization Model. The Interaction Model is completed with preconditions, task flows executions and their effects on the environment and on interacting holons. The Sustainability Guidelines 1 through 3 from Table 2 are key for completing this step. This bottom-up process must be repeated until the system engineer reaches the highest cooperation domain in the Analysis Models.

A decision flow diagram (Giret et al., 2015) supports Design Guideline 1 enforcing the system engineers to think about their main designs choices when designing Go-green Holon (i.e. the best categories for each of the sustainable parameters taken into account in the SIMS). The decision flow takes into account: the sustainable means that must be optimized; the type of approach required (offline – before production; online – able to adapt and react to run-time events during production; or a mixed approach – a combination of the other two); and the hard and soft constraints that must be satisfied. The last requirement will determine the way the multi-objective must be handled. The decision support provided by Go-green ANEMONA help the system engineer to chose from the library of pre-built solving approaches the one that better suits the specific sustainability requirements of the system being developed (see (Giret et al., 2015) for a list of approaches suitable for different sustainable requirements combinations).

### Step 2: Build System Architecture

The goal of this last design step is to completely specify the System Architecture including details of the target implementation/execution platform. In the specialized literature there are many agent execution platforms that can be used and Go-green ANEMONA provides different sets of guidelines for different platforms. For high-level control (intra-holon information processing and inter-holon cooperation) Go-green ANEMONA provides design guidelines for JADE – Java Agent Development Framework (<http://jade.tilab.com>) and SIMBA (Julian and Botti, 2004). For the specification of holons with physical processing part (machines, resources, etc.) the methodology provides Function Block Guidelines.

The result of this step is the System Architecture composed of the Design Models (built in the previous step), the JADE Agent Templates, the SIMBA Specification and the Function Block Interface Specification. A JADE Agent Template is built for each holon in the Design Models. A SIMBA Specification is completed for every holon with hard real time constraints and with no physical processing part. The Function Block Interface Specification is produced for the physical processing part of each holon representing physical processes, equipment or machines. The UML Deployment Diagram models the physical architecture of the different system nodes, the agent platforms and the allocation of containers.

#### 3.2.3. Go-green ANEMONA implementation, Setup and configuration phases

The input of the Holon Implementation phase is the System

Architecture and the goal of this phase is to produce the Executable Code for the SIMS. In this phase the system engineer has to implement the information processing part of the holons and the physical processing part of each holon representing physical processes, tools or machines. The Sustainability Guidelines 1 and 2 from Table 3 are specially tailored for helping the system engineer to implement the required sustainable processes by Go-green Holons. The main objective of this set of guidelines is to implement the mechanisms for measuring the targeted KPIs. The Go-green ANEMONA CASE tool provides a library of pre-built solving methods for different implementations of efficiency-oriented objectives, constraints and KPIs of Go-green Holons. Configuration activities are carried out in the Setup and Configuration phase to deploy the SIMS at the target destination factory floor. Finally in the Operation and Maintenance phase the necessary maintenance activities are carried out. In the case of new or modified requirements, a new development process must be started.

#### 3.3. Development tools

Go-green ANEMONA provides: a complete CASE tool to graphically design SIMSs; a set of automatic code generation modules that generate code from the models designed with the CASE tool, and; a set of different prebuilt solving approaches for manufacturing operations scheduling subject to efficiency-oriented objectives, constraints and KPIs.

The CASE tool is an extension of the EMFGormas CASE tool and is available to be downloaded at <http://users.dsic.upv.es/grupos/ia/sma/tools/EMFGormas/>. Fig. 6 shows a snapshot of the CASE tool where its main parts are highlighted.

## 4. Validation of Go-green ANEMONA

In this section we present a set of case studies that were performed in order to test different features of Go-green ANEMONA. The three different case studies have different validation goals.

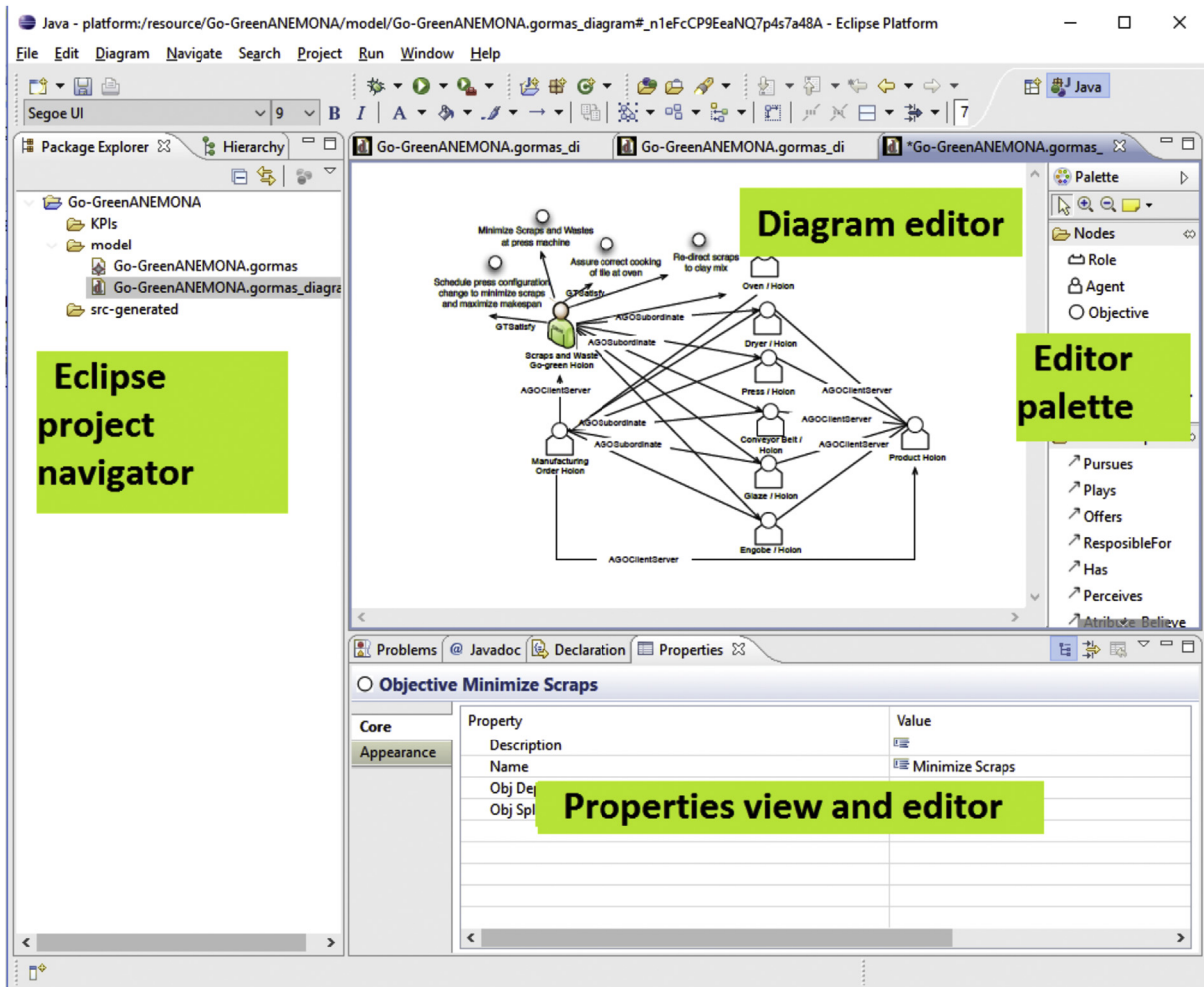
Case study 1: A ceramic tile factory application in which the SIMS is tailored to control production optimizing sustainability features. The goal of this case study is to assess the following features of the Go-green ANEMONA development process: time to design, easy to design, guidelines usefulness, number of holons and number of cooperation domains.

Case study 2: A plastic production by injection molding SIMS in which Go-green ANEMONA is used to design an energy aware approach for the intelligent off-line scheduling of the manufacturing operations. The goal of this case study is to assess the quality of the solutions derived with Go-green ANEMONA.

Case study 3: An academic full size real flexible manufacturing system (FMS) for which the method is used to add new sustainable features to a running application in order to adapt to new requirements. The goal of this case study is to assess the usefulness of Go-green ANEMONA when a system must be augmented in order to add more sustainability features and optimization criteria.

**Table 3**  
Sustainability guidelines for the implementation phase.

Sustainability guidelines for the implementation phase
1. Implement the Go-green Holons using the programmer's library for sustainable processes.
2. For every cooperation scenario execute validation and verification tests in order to measure the KPIs.



**Fig. 6.** Snapshot of the Go-green ANEMONA CASE tool.

#### 4.1. A ceramic tile factory intelligent manufacturing system

In this case study an intelligent distributed monitoring and control application of a ceramic tile factory is designed using Go-green ANEMONA. In this system the sustainable goals to optimize are: minimize scraps and waste due to bad quality of the tiles; and minimize energy consumption re-using the oven residual heat in the tile drying step of the production line. The SIMS must also minimize the makespan.

The goal of this case study is to assess the following features of the software development process: time to design, easy to design, guidelines usefulness, number of holons and number of cooperation domains. To this end, two different development teams (with the same number of members and with the same background on software engineering) developed different two different SIMS for the ceramic tile factory case study. One team used Go-green ANEMONA, and the other used ANEMONA without the specific guidelines and without the Go-green Holons. The two teams derived all

five models in order to build the system that fulfills the mentioned goals. Due to space limitation in this paper we cannot present all the models of the system. Nevertheless, Fig. 7 shows a diagram (from the Go-green ANEMONA team) in which the Scraps and Waste Go-green Holon is specified. In this figure the relationships that this GGH maintains with the other holons of the system, an interaction sequence, and the goals of the Scraps and Waste GGH are depicted. Thanks to the Sustainability Guideline for the Design Phase 1 (Table 2), the Scraps and Waste GGH provides a solving approach for scraps and waste minimization based on a meta-heuristic search technique (Escamilla et al., 2014). With this approach the holon finds out the optimized sequence of work orders for minimizing scraps due to press configuration change. This solving approach is implemented in the Adjust Resource task of Fig. 7.

Table 4 shows the results of the validation test with the two development teams in order to measure five features of the development process.

4.1.1. Discussion and lessons learned

From the results of the validation tests presented in Table 4 it can be noticed that the number of iterations of the development process, used by both teams, are the same, but when taking into account Time to Design Go-green ANEMONA outperforms ANEMONA by 0,5 months. In order to assess Easy to Design and Guidelines Usefulness it was used MASEV (Garcia et al., 2011) (a MAS evaluation framework). This framework analyzes and compares methods and tools for developing MAS. MASEV uses a questionnaire for the aspects that are evaluated, and calculates a numerical value with respect to the answers provided to the questionnaire. Go-green ANEMONA got 9,5 out of 10 when evaluating the usefulness of Go-green Holons (Easy to Design) with MASEV. The Guideline Usefulness for designing SIMS of Go-green ANEMONA has been evaluated at 9,2 out of 10. On the other hand, Go-green ANEMONA identified more holons than the classical ANEMONA method, a total of 8 more holons. This is due to the

GGHs are added to the classical holons in the development. But this larger number of GGHs has reduced the number of cooperation domains to 28 from a total of 34 from the classical ANEMONA. This fact is due to the simplification introduced with GGHs by concentrating all the sustainability-efficiency related capabilities and interactions to the cooperation domains in which the GGHs are involved, and, in this way, eliminating the need to have dedicated cooperation domains for sustainability issues. Gaining in terms of cooperation domain configuration, initialization, execution and deletion.

From this validation case study we can conclude that Go-green ANEMONA simplifies the integration of sustainability considerations during the design phase of intelligent manufacturing control systems and leads to the design of more compact SIMS (in terms of number of computational entities with the same overall functionality) in less time.

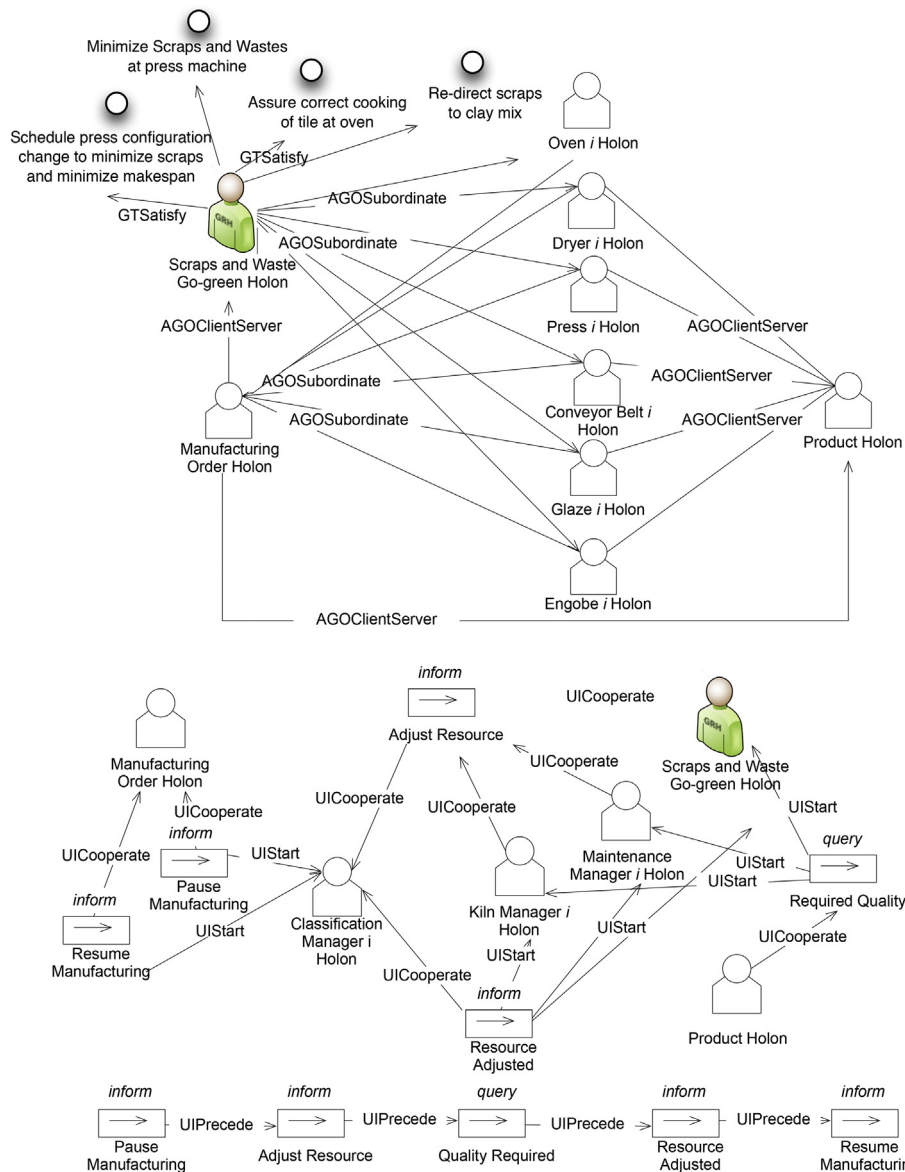


Fig. 7. Goals of the Scraps and Waste Go-green Holon, its relations with classical holons, and a cooperation diagram for controlling a tile pressing, painting, cooking and quality classification line.

**Table 4**

Case study comparison: ANEMONA vs. Go-green ANEMONA.

Method	Time to Design	Easy to Design	Guidelines Usefulness	Number of Holons	Number of Cooperation Domains
ANEMONA	3 method iterations (3 months)	7,5/10	7/10	46	34
Go-green ANEMONA	3 method iterations (2,5 months)	9,5/10	9,2/10	54	28

#### 4.2. An intelligent production scheduling system for an energy intensive manufacturing system

In this case study a plastic production by injection molding is considered. This industry pertains to the set of greatest energy consumer industries (a total of 2.06 108 GJ per year for this industry in USA). The problem to be solved is the off-line scheduling a set of orders on a set of parallel injection molding presses. A product type and a penalty cost for late delivery characterize each order. Alternative presses are available for each order and the order-machine pair has an associated processing time and energy consumption. Setup times between two successive operations on the same injection press must be considered due to the need to perform mold change and cleaning after an operation finishes. Therefore, this case is considered as a multi-objective scheduling problem in which the total tardiness, total setup time and total energy consumption must be minimized.

The goal of this case study is to assess the quality of the solutions derived with Go-green ANEMONA. To this end Go-green ANEMONA is used to design a MAS model for solving the above-described problem and the solution obtained is compared with a centralized approach (based on mixed integer programming - MIP) that solves the same problem.

The Sustainability Guidelines together with the Go-green ANEMONA process steps help to derive a distributed model that includes a team of Go-green Scheduler Holons managed by a Go-green Master Holon. Moreover, the solving approach used by the Go-green Scheduler Holons in order to solve the multi-objective scheduling problem assigned to them is derived from the decision-flow proposed in (Giret et al., 2015).

The overall idea under the derived MAS model is to use a Go-green Master Holon to decompose the problem into sub-problems that are delegated to Go-green Scheduler Holons for solving them. Then, the Go-green Master Holon composes a global solution from the partial solutions provided by the Go-green Scheduler Holons.

Every Go-green Scheduler Holon is responsible to manage an individual press machines and is committed to solve a partial problem by scheduling all jobs assigned to that machine. The Go-green Scheduler Holons receive their partial problems and use a MIP approach (Tonelli et al., 2016) built from their own local variables. On the other hand, the Go-green Master Holon is committed to distribute the problem into sub-problems and carry out the coordination among the Go-green Scheduler Holons to compose the global solution. To this end, the Go-green Master Holon receives the problem instance specification and generates as many Go-green Scheduler Holons as parallel machines are involved in the problem.

Moreover, the Go-green Master Holon is able to balance the workload of Go-green Scheduler Holons to avoid a bottleneck or energy constraints in a given Go-green Scheduler Holon. Once all jobs are distributed between the Go-green Scheduler Holons, the Go-green Master Holon is able to determine the total energy consumption of the resultant solution. This is possible because all jobs have been distributed and thus the energy consumption of each job is assigned. This issue is key for the MAS model derived from Go-green ANEMONA since the user knows in advance the total energy consumption required by each machine. Thus, if there are

energy constraints for the machines, these constraints can be included in the Go-green Master Holon knowledge.

Fig. 8 depicts the interaction sequence among the holons. The list of exchanged messages and their sequences are shown in this figure. The time and the execution thread of each holon are represented by the vertical line (from each holon) in the diagram. Message passing from one holon to the other is depicted using arrows between the two holons. In a message, the sending holon can request the execution of a given function from the receiving holon, or can inform the receiving holon a given data.

The MAS distributed solver developed with Go-green ANEMONA was compared with a centralized approach (based on MIP) that solves the same scheduling problem. The evaluation was done comparing the two solvers, through simulations, in order to assess their efficiency, scalability and solution quality (Tonelli et al., 2016). Fig. 9 shows the results of the evaluation. The number of jobs  $n$  and involved machines  $m$  define the instances presented in the figure as a tuple  $(n,m)$  on the X axis. Four different sets of 125 instances were generated. The MIP and Go-green ANEMONA MAS solver executed all instances on a 2.4 GHz Intel Core 2 Duo with a 3600 s timeout.

##### 4.2.1. Discussion and lessons learned

Fig. 9 depicts the variation (in percentage) of the different objectives (tardiness, setup time and energy consumption) of the MAS model obtained with Go-green ANEMONA against the MIP approach. The MAS model obtained a better behavior in total tardiness and energy consumption in almost all instances, whereas the MIP model outperformed the MAS model in setup times. This fact is justified because the Go-green Master Holon selects the jobs that can be assigned to different machines (shared jobs) according to the energy consumption and processing time. However the Go-green Master Holon cannot consider the setup time because the machine sequence is not known in advance. In summary, the quality of the obtained solution from Go-green ANEMONA is better when comparing it to a MIP based approach.

#### 4.3. Adding sustainability value to an energy-aware flexible manufacturing system

In this case study an academic full size real flexible manufacturing system (FMS) is used in order to adapt/augment a running application to new sustainable requirements. The FMS is located at the University of Valenciennes and Hainaut-Cambrésis and is called AIP-PRIMECA FMS (Trentesaux et al., 2013). This FMS is built around a central conveyor belt with transfer gates to reach the resources or to move from one loop to another. Auto-propelled shuttles that transport products through the cell use this conveyor that can be modeled as a 1D directed graph. In front of each transfer gate, a "divergent node" (seen as a decisional node) position the transfer gate either to reach a resource or to another loop. The problem to address (called dynamic scheduling of a flexible job shop with recirculation) is to solve the dispatching order of the jobs, the machine allocation for each job and the routing path of the job in the conveyor system.

The goal of this case study is to assess the usefulness of Go-green ANEMONA when a running system must be augmented in order to add more sustainability features and optimization criteria. To this

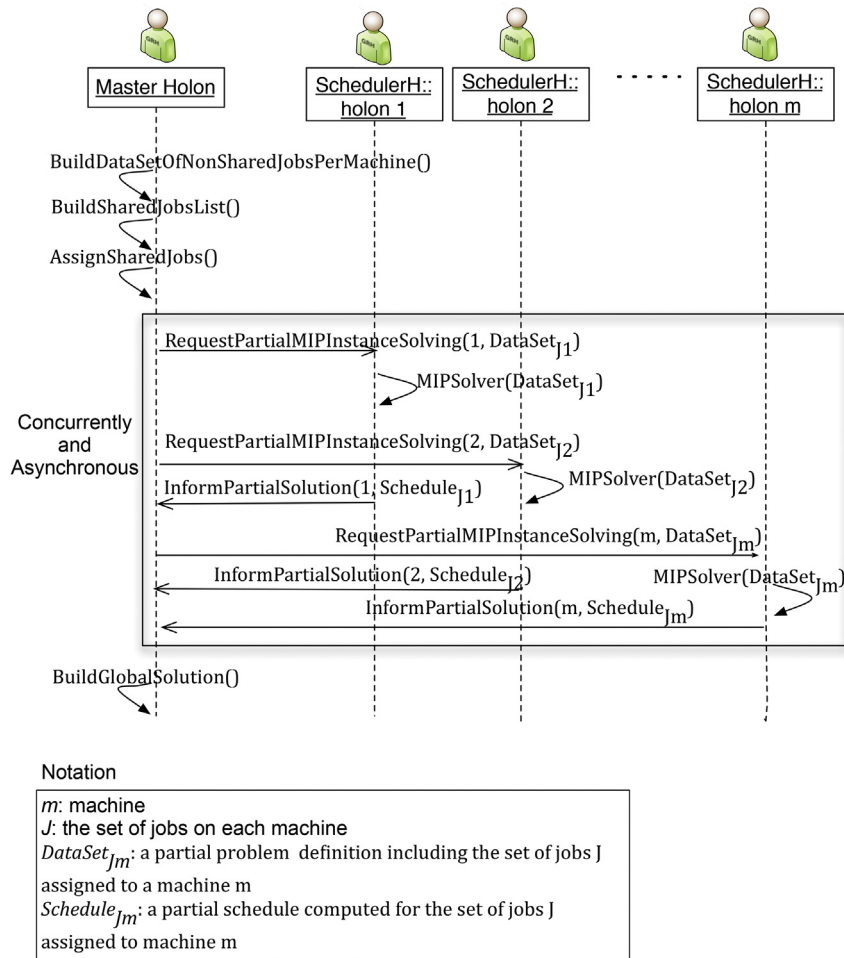


Fig. 8. Interaction diagram to solve the distributed scheduling problem.

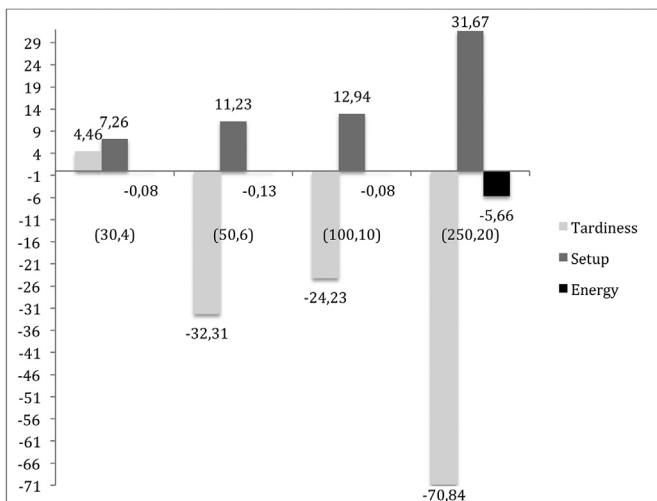


Fig. 9. Percentage variation of average tardiness, setup time and energy consumption with respect to different classes of instances solved with the MAS model and the centralized MIP approach.

end Go-Green ANEMONA is used to improve the energy-aware intelligent control system discussed in the state-of-the-art section (Pach et al., 2015) and to solve the described limitations. Fig. 10 shows the hybrid FMS distributed model derived with Go-Green

ANEMONA. This model extends the initial work of Pach et al. with predictive scheduling capabilities and balancing makespan/energy consumption mechanisms. In this design it can be noticed four types of holons. PF Product Holon and PF Resource Holon are green manufacturing holons inherited from the model proposed in (Pach et al., 2015) and extended with predictive scheduling capabilities using Sustainability Guideline 6. On the other hand, Work Order Holon is responsible of activating the system from a work order description, that includes the list of products to be produced, the makespan, the energy threshold for the complete system and an energy availability forecast for a given time period (the time period includes finish time of the sequence of jobs for producing the products in the order). The Off-line Scheduling Manager Holon is a green manufacturing holon designed to decompose the original problem and to distribute its solution to the concrete PF Resource Holons involved and finally composing a global predictive schedule for the FMS. Off-line Scheduling Manager Holon is responsible for taking into account the overall energy threshold for the system; break it down into individual thresholds and then communicate them to the PF Resource Holons. In order to cope with the global energy threshold criterion, a distributed Constraint Satisfaction Problem (CSP) approach where energy constraints are propagated locally to the PF Resource Holons is followed. This is done because the PF Resource Holons do not have a complete picture of the energy being consumed and/or available in the system for a given time but the Off-line Scheduler Manager does. In this way the PF Resource Holons can locally schedule the jobs trying to minimize

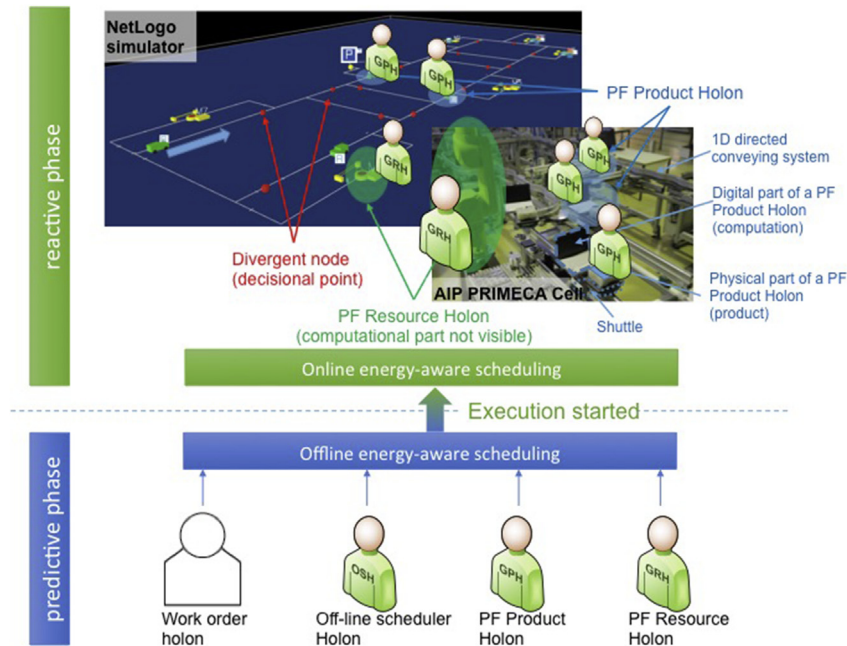


Fig. 10. Hybrid FMS distributed model derived with Go-Green ANEMONA (Netlogo simulator and corresponding AIP PRIMECA cell “proof-of-concept” implementation).

the energy consumption maintaining the hard constraint of their local energy threshold.

Fig. 11 depicts the interaction diagram of the proposed distributed problem solving. It is divided in two phases: an offline/predictive scheduling and an online/reactive scheduling. In the first phase, an initial energy-aware schedule is obtained, in a distributed fashion, by an Off-line Scheduling Manager Holon and a set of PF Resource Holons. Thanks to Go-green ANEMONA’s Sustainability Guideline 6 it was possible to derive a model in which the set of involved holons maintains the scheduling effectiveness (makespan) as the main objective, while minimizing the energy consumption. This criterion states that in any situation the multi-objective is to:

$$\begin{aligned} & \text{minimize}(\text{Makespan}, \text{EnergyConsumption}) \text{ s.t} \\ & (\text{Makespan} < \text{Threshold}_{\text{Makespan}} \text{ And} \\ & \text{EnergyConsumption} < \text{Threshold}_{\text{Energy}}). \end{aligned} \quad (1)$$

Moreover, every PF Resource Holon is augmented with a new predictive capability for off-line scheduling in a robust way to cope with possible perturbations and taking into account the energy availability forecast when solving the schedule. In the second phase, the Work Order Holon launches the schedule obtained in the first phase informing the PF Product Holons and the PF Resource Holons of the system.

In this way, the PF model proposed in (Pach et al., 2015) is used to cope with the dynamic events that might appear at run time, such as new orders entering the system, resources’ breakdown, changes in jobs priorities, etc. The offline phase complies with the total available energy threshold taking it as a hard constraint when: calculating the individual thresholds for the PF Resource Holons, and; composing the global solution from the schedules provided by the PF Resource Holons. Whereas during the online phase the PF model is responsible of assuring the compliance with this threshold until this one starts to vary due to unexpected reasons. In that case, and to avoid stopping production waiting for a new schedule, the off-line schedule is canceled and the initial PF model proposed by Pach et al. takes the responsibility for the scheduling of the

remaining tasks to comply with, in real time, this varying threshold until the set of orders is finished.

#### 4.3.1. Discussion and lessons learned

Starting from the original model proposed in (Pach et al., 2015) the Sustainability Guidelines and the HMS Guidelines provided by Go-green ANEMONA helped to end-up with a system in which the original components were reused and few new elements were added in order to comply with the new sustainability requirements. Moreover, using the Go-green manufacturing Holon artifacts it was easy to communicate the new holons with the original components of the system. The validation tests performed for this case study were undertaken at conceptual level and through simulation. It is important to point out that this case study is still under development, despite that it has already enabled us to validate the feasibility of the reactive phase, that is, the embedded elements and their interactions, being PF products and resource holons. This validation of the feasibility has been made from a technological point of view, which was the critical part of the implementation (the development of the predictive phase on a single computer does not present any critical risk). Despite being a partial validation it can be concluded that the gaining from using Go-green ANEMONA were valuable in terms of: (i) time to design (two weeks); (ii) low number of modifications required in the original system structure (only one new holon, the Off-line Scheduling Manager Holon, and one new function in every PF Product Holon and PF Resource Holon); (iii) analysis and design activities focused mainly on the new system features (off-line phase) instead of focusing on the overall system; (iv) reuse of the reactive capabilities of PF Product Holon and PF Resource Holon from the previous model. Meanwhile and in addition, as introduced, the lessons learned from these experiments concern only a proof of concept and not a real viable industrial system. Efforts must be pursued in that direction, including analyzing the deployment costs (along with a ROI study) using real industrial technological solutions, as well as the reliability, the robustness and the ability to guarantee the sustainable performances indicators of the proposed Go-green ANEMONA method.

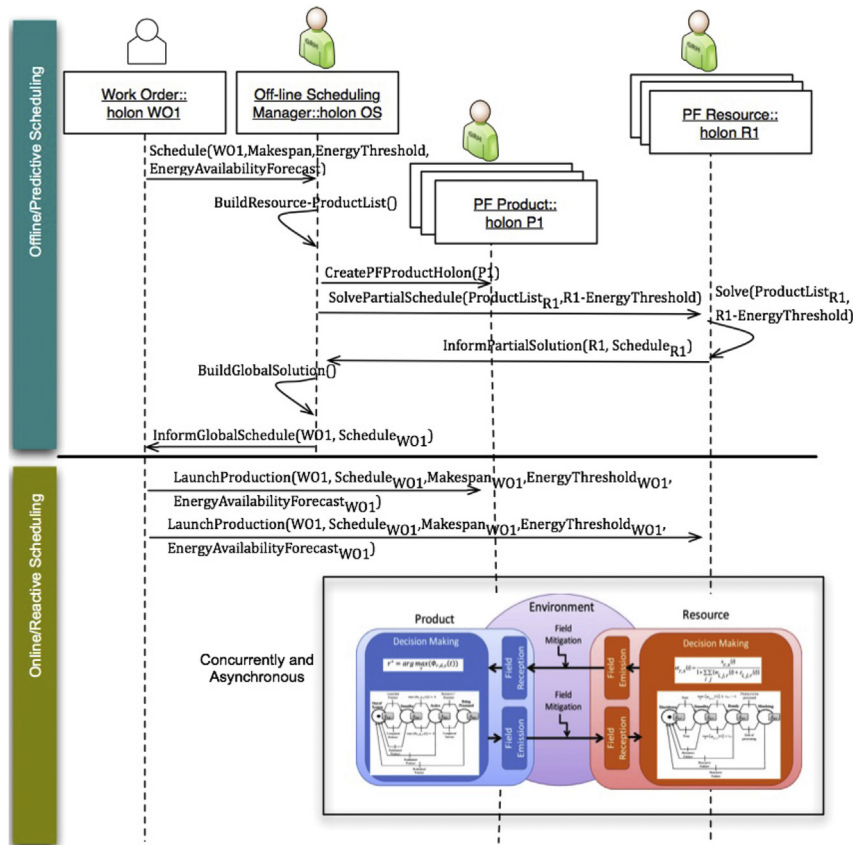


Fig. 11. Interaction diagram for a hybrid energy-aware FMS model.

## 5. Conclusions and future works

In this paper two questions for developing sustainable manufacturing systems were dealt with. In the first part of the paper question Q1: what features are key to integrate sustainability efficiency when designing IMS? was analyzed describing the features of sustainable manufacturing systems and the state-of-the-art on approaches for developing them. In the second part of the paper question Q2: can these features be integrated using concepts from IMS engineering methods? was treated. We answered this last question proposing a concrete software engineering method that helps developers to develop sustainable intelligent manufacturing systems named Go-green ANEMONA. Go-green ANEMONA is the integration of a previously released and already sound Multi-agent engineering method for Intelligent Manufacturing Systems (Giret and Botti, 2009), and the new Go-green manufacturing Holon concept (Trentesaux and Giret, 2015) that helps system engineers to achieve sustainability features into manufacturing operations control architectures. Go-green ANEMONA provides the methodological benefits of HMS and MAS approaches for the identification and specification of sustainability specific features of manufacturing systems. It is guided by the identification of the manufacturing holons and the design and integration of sustainability-oriented mechanisms in the system specification.

Go-green ANEMONA provides full support for system engineers that need manufacturing specific guidelines and sustainability specific analysis/design activities and constructs for developing SIMS operations architectures.

The proposal was showcased designing three different use cases in order to: (i) assess some features of the Go-green ANEMONA

software development process, such as: time to design, easy to design, guidelines usefulness, number of holons and number of cooperation domains; (ii) assess the quality of the solutions derived with Go-green ANEMONA, and; (iii) assess the usefulness of Go-green ANEMONA when a system must be augmented in order to add more sustainability features and optimization criteria. These validation cases demonstrated the usefulness of Go-green ANEMONA when dealing with large-scale problems, the better performance of the distributed solution derived with Go-green ANEMONA compared with centralized approaches and, the seamless integration of new elements into production control solutions.

In order to complete the set of tools provided by Go-green ANEMONA, the library of pre-built solving methods for the efficiency-oriented objectives, constraints and KPIs of Go-green Holons is being extended. Another important ongoing work in order to complete Go-green ANEMONA is to develop a set of wrappers and/or gateways to seamlessly connect the green components such as go-green Holons and sustainable KPIs with information systems of the enterprise management level such as ERP, MES and SCADA systems. Moreover, extended validation case studies are required in order to test Go-green ANEMONA correctness when dealing with real industrial scenarios that involve thousands components and a large number of sustainable features to optimize. Energy intensive manufacturing industries are worth to consider since the reduction in energy consumption can tremendously impact the companies revenue and the effects on the environment. Finally, further work is required to extend Go-green ANEMONA in order to properly support the development of sustainable supply chain and logistics.



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