Go-green ANEMONA: a holonic multi-agent methodology to design sustainable intelligent manufacturing control systems

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Abstract:

Nowadays manufacturing companies need to achieve overall sustainability in industrial activities at the same time that they face unprecedented levels of global competition. Therefore there is a well-known need of support for designing and implementing systems that deals with these issues. It is crucial and urgent for the system engineers of sustainable manufacturing systems to have tools and methods that can help them to undertake this task from system conception, throughout its design until its execution in an effective way. This paper proposes an engineering method that helps researchers to design sustainable intelligent manufacturing system. 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 guidelines and tools with built-in support for sustainable features. Besides a set of case studies are presented in order to assess the proposed method.

Keywords: Sustainability, Multi-agent systems, Holonic control, Manufacturing, Design method

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1. Introduction

There is now a well recognized need for achieving overall sustainability in industrial activities (Garetti and Taisch, 2012)(Fang et al., 2011)(Merkert et al., 2015), arising 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.. One of the key questions to answer in the field of Sustainable Production is: What approaches should/could be used to transform production processes to be more sustainable? 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 presented in (Salonitis and Ball, 2013) the new challenges imposed by adding sustainability as a new driver in manufacturing modeling and simulation. Moreover, it was also pointed out that is crucial and urgent for the system engineers of sustainable manufacturing systems to have tools and methods that can help them to undertake this task from system conception, throughout its design until its execution in an effective way.

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 among them 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 agents allows an equitable resource allocation (like energy allocation) that can lead to a "social welfare" (Chevaleyre 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 paying attention to sustainability issues at design phases of the IMS. In this context, this paper specifically deals with two key questions: (Q1) What are the needs to integrate sustainability efficiency performance in IMS design? (Taticchi et al., 2013)(Taticchi et al., 2015); (Q2) How can these needs be approached using concepts from IMS engineering methods in the context of design of sustainable manufacturing systems?

The above-mentioned questions motivate this work and in this paper we propose an engineering method that helps researchers to design Sustainable Intelligent Manufacturing System (SIMS). This 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 and already sound Multi-agent engineering method for IMS (Giret and Botti, 2009), and the new go-green holon (GGH) concept (Trentesaux and Giret, 2015a) that fosters system designers to achieve sustainability features into manufacturing operations 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 rest of the paper is organized as follows. Section 2 summarizes the theories and works that motivate Go-Green ANEMONA. Section 3 presents Go-Green ANEMONA method. 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.

2. Related works

The main objective of our work is to provide support for systems engineers that are seeking to implement manufacturing systems that are sustainable and intelligent. 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 in order 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

The United Nations Brundtland Commission widely introduced the definition of sustainable development 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 is a challenging and complex task involving many factors such as technology and engineering, economics, environment, health and welfare of people, social desires, and government strategies, procedures and policies. Sustainability can thus be viewed as having three pillars: environmental, economic and social (including political).

Regarding industrial processes, the main initiatives of the nations focused on restricting the adverse environmental impacts of energy consumption. In the past, the economic aspect of sustainability was the main focus, whereas corporations have recently started to address environmental sustainability. Nowadays, in the light of stricter legislation, industrial standards, and rising energy costs, companies are not only required to adopt a minimal environmental compliance strategy, but also to consider sustainability practices as a catalyst for innovation and competitiveness (Zampou et al., 2014). This very complex and challenging undertaking must also consider issues at all relevant levels in manufacturing – product, process, and system (Jayal et al., 2010). 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 (Merkert et al., 2015).

In order to focus on a given notion of sustainable manufacturing, the definition of sustainable manufacturing provided by the US Department of Commerce (International Trade Administration, 2007) was adopted in this paper: "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". Several notions are often used to describe strategies or philosophies that are more or less similar in the context of sustainability in manufacturing: lean[1], clean, green manufacturing to name a few.

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 values that are difficult to calibrate. Salonitis and Ball presented in (Salonitis and Ball, 2013) the new challenges imposed by adding sustainability as a new driver in manufacturing modeling and simulation. It is crucial and urgent for the system engineers of sustainable manufacturing

[1] 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).

systems to have tools and methods that can help them to undertake this task from system conception, trough out its design until its execution in an effective way. One of the major challenges in developing such approaches is the lack on guidelines and tools that foster the system designer to consider sustainability issues at design phases and that can help during the implementation of the sustainable manufacturing system.

Many manufacturing paradigms promise to meet the challenges of the factories of the future (Shen et al., 2006) such as: enterprise integration, distributed organization, heterogeneous environments, interoperability, open and dynamic structure, cooperation, integration of humans with software and hardware, agility, scalability, fault tolerance, and, last but not least, sustainability (lately added to this already large list). Two of these paradigms, Distributed Intelligent Manufacturing Systems, and Holonic Manufacturing Systems have recently been attracting a lot of attention in academia and industry. Distributed Intelligent Manufacturing Systems, or agent based manufacturing systems, are based on Multi-Agent System (MAS) technology (Castelfranchi and Lesperance, 2003). MAS studies the coordination of intelligent behaviors among a group of (possibly pre-existing) agents. Today MAS is a very active area of research and is beginning to have commercial and industrial applications. Holonic Manufacturing is based on the concept of "holonic systems", developed by Arthur Koestler (Koestler, 1990). Koestler proposed the word holon to describe the hybrid nature of sub-wholes/parts in real-life systems; holons are simultaneously self-contained wholes to their subordinated parts, and dependent parts when seen from the inverse direction. Work in the HMS program has translated these concepts to the manufacturing world, viewing the manufacturing system as consisting of autonomous modules (holons) with distributed control. The HMS concept combines the best features of hierarchical and heterarchical organization (Dilts et al., 1991). It preserves the stability of hierarchy while providing the dynamic flexibility of heterarchy. In a HMS a holon is an autonomous and co-operative manufacturing system building block for transforming, transporting, storing and/or validating information and physical objects. The holon consists of an information processing part and often a physical processing part (Christensen, 2003). A holon can be part of another holon.

In the last ten years, an increasing amount of research has been devoted to HMS over a broad range of both theoretical issues and industrial applications. McFarlane and Bussmann have divided these research efforts 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.

Very 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 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, 2015b) 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 (Capera et al., 2003) that aims to design adaptive agents, which avoid none cooperative situations (NCS). 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-leveled 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 Depeisse 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 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

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. Lastly, 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 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. 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). 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 support this claim by means of:

- Specific guidelines based on lean and sustainable manufacturing that can help the system designer to figure out (1) what sustainability parameters are key to the system, (2) how these parameters must be taken into account by the components of the SIMS, (3) when these parameters must be used for achieving sustainability efficiency in the system, (4) which approaches can be used to compute a sustainable solution for the different tasks and processes of the manufacturing system.
- "Green" artifacts that can provide optimized solutions for concrete aspects at different levels such as: enterprise resource planning, production control, manufacturing operations scheduling, etc.

The above-mentioned aspects, which are some answers for Q1, are the main focus of this paper. Moreover, this paper answers Q2 by means of Go-green ANEMONA. It is important to point out that we believe that the answers provided, in this paper, for Q1 are two of a larger list. Finding out, which are the complete elements of this list, is outside of this paper and an open problem worth to a deeper study. In this paper the complete details of the sustainable specific guidelines and green artifacts to assist the system engineer during the SIMS design are described. Moreover, the engineering process is showcased with case studies.

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 thought out three different case studies.

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 sustainable manufacturing operations architectures.

Go-green ANEMONA is a complete software engineering approach for Sustainable Intelligent Manufacturing Systems (SIMS) 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 sustainable manufacturing systems. Go-green ANEMONA includes a new set of guidelines and integrate into its metamodel the concept of Go-Green Holons (GGH) (Trentesaux and Giret, 2015b).

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 summarizes 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 IMS in terms of holons, 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. Figure 5 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). The main elements of the metamodel that support the Go-green ANEMONA features are: Go-green Holons, associated with efficiency oriented KPIs, and efficiency oriented objectives and constraints.

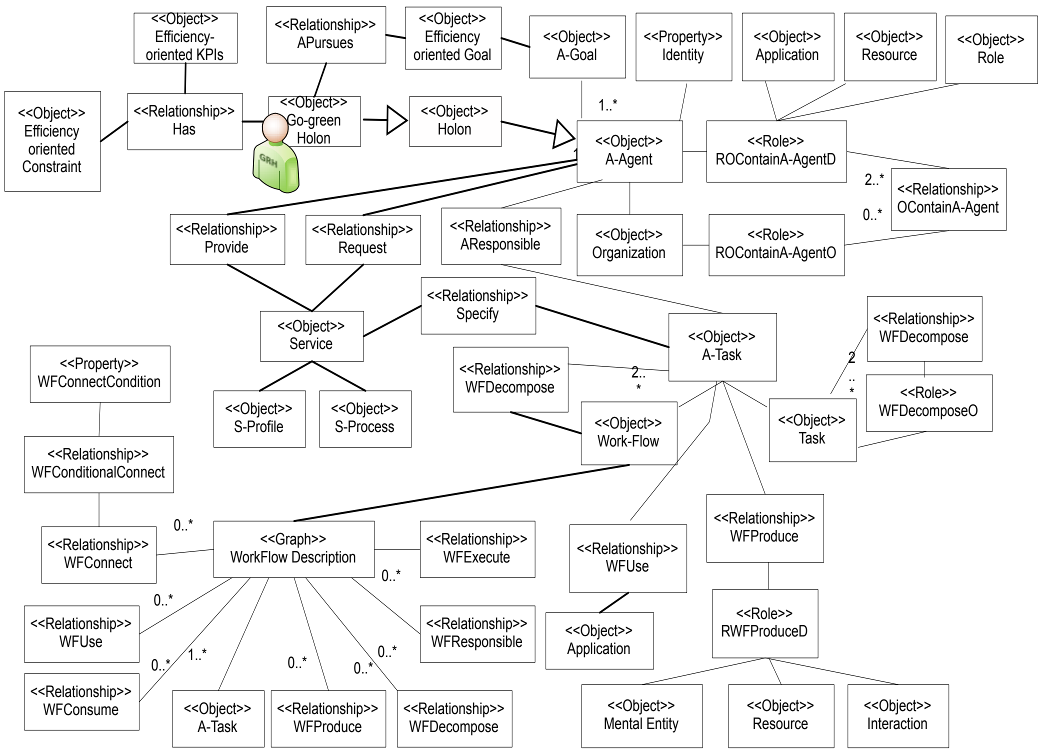

Figure 1: Fragment of the metamodel of Go-green ANEMONA

A Go-green manufacturing Holon (Trentesaux and Giret, 2015b) is a holon that, in the context of sustainable manufacturing, considers complementary efficiency-oriented mechanisms, 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. Figure 2 shows an example of a Go-green (manufacturing) resource Holon that integrates concrete 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.

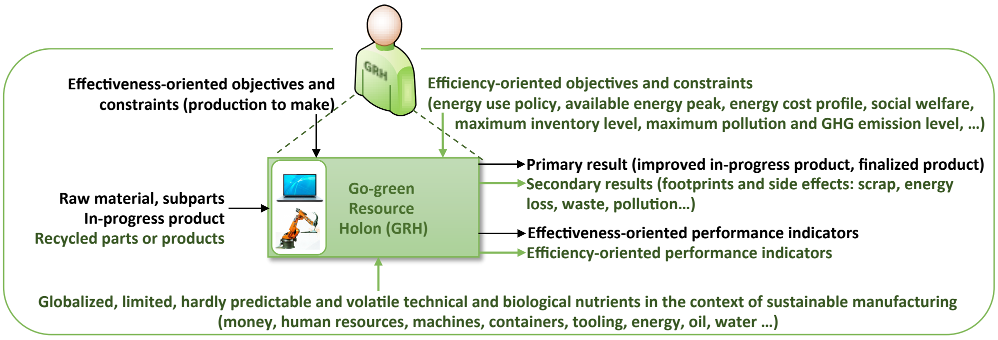

Figure 2: A Go-green Resource Holon

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 dividing into more specific characteristics that form different views of the system. 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 interact with other non-autonomous. (5) The *task/goal model* describes relationships among goals and tasks, goal structures, and task structures.

3.2 Software development process[2]

Go-green ANEMONA software development process guides system engineers during the analysis, design, implementation, setup and configuration of sustainable manufacturing systems. 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

[2] 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.

main designs 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 guidelines to help the designer in identifying and implementing holons. Figure 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 to specify, analyze, design, implement, deploy and maintain the SIMS. Every step in the process is augmented with a set of specific guidelines for concrete aspects during the system development. At the same time, at each step during analysis, design, implementation, deployment and maintenance it is provided a specific artifact, the Go-green Holon, which the system engineer can use and/or augment 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).

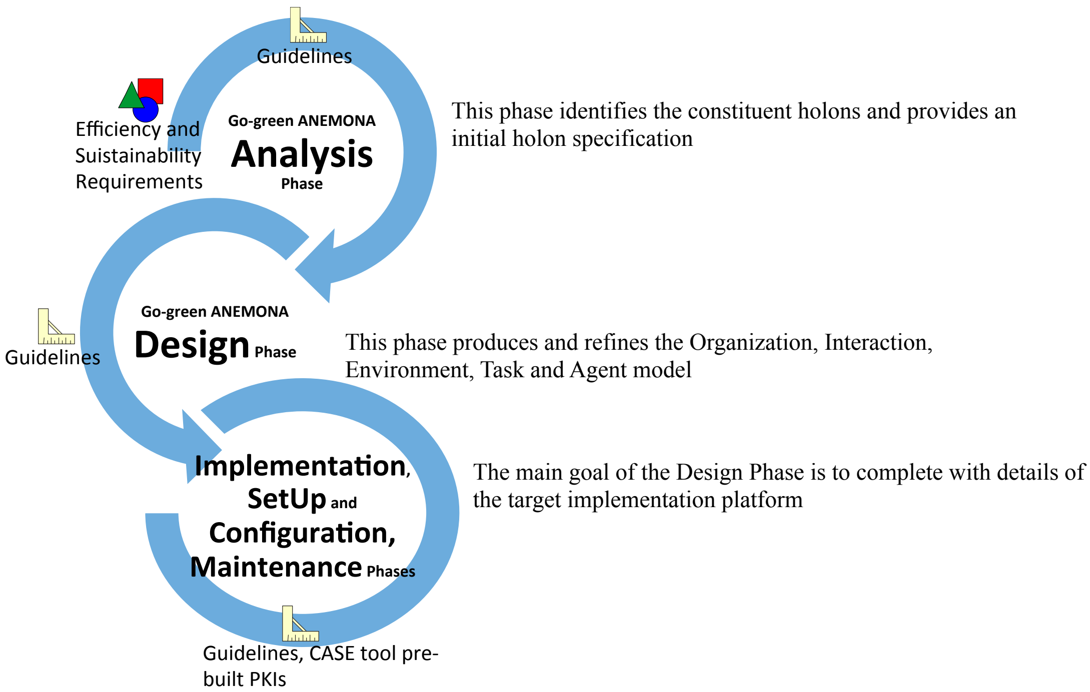

Figure 3: Go-green ANEMONA process

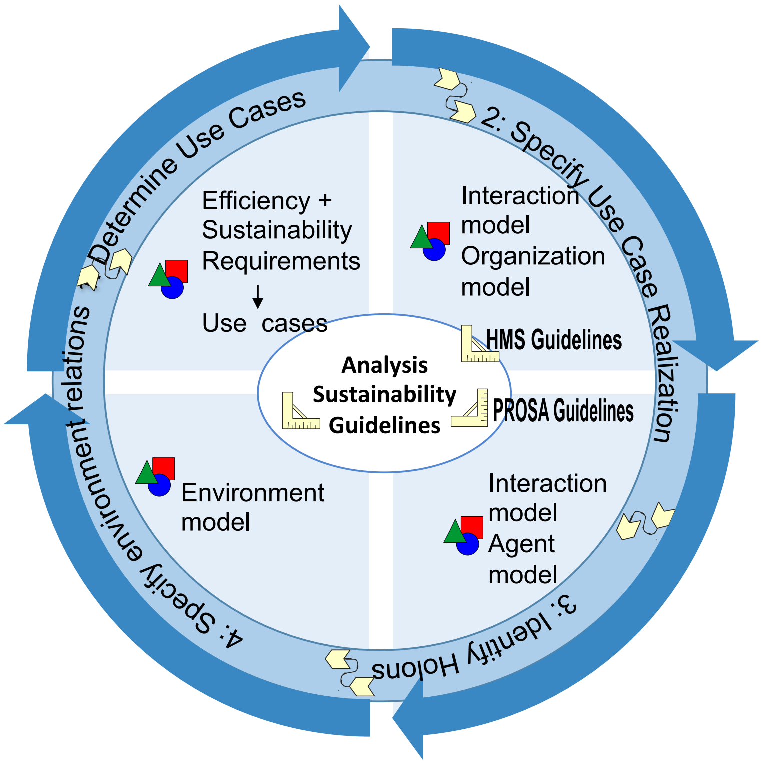

Figure 4: Analysis phase of Go-green ANEMONA

3.2.1 Go-green ANEMONA Analysis Phase

The main goal of the analysis phase is to identify the constituent holons and to provide an initial holon specification. 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[3] 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. As is shown in Figure 4, this phase is devised as 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 manufacturing systems since complex and large-scale problems can be analyzed using different abstraction levels, thanks to the recursivity feature of holons. To this end the analysis phase of Go-green ANEMONA follows a rapid iterative approach in order to find out a first holonic structure in every abstraction layer. This approach reduces excessive 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. At the end of every iteration, the system engineer must analyze each holon in order to figure out the advantages of decomposing it into a new holarchy. In this way, each new iteration will have, as many concurrent and collaborative processes as constituent holons of the previous iteration, which it was decided, would be decomposed. This process is repeated until every holon is defined and there is no need for further decompositions.

[3] 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.

A Go-green ANEMONA analysis iteration 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 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.

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 principles 4: 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, CO_2, 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.

Table 1. Sustainability Guidelines for the Analysis Phase

STEP 3: Identify Holons

The designer works with the work products of the previous step, the system Requirements, the PROSA Guidelines (Giret and Botti, 2009) and the Sustainability Guidelines to identify any new holon and to categorize the identified holons.

The PROSA Guidelines are defined based on PROSA types of holons (Van Brussel et al., 1998). Based on the PROSA Guidelines the designer must refine both the Organization model and the Interaction model by adding new or modified relations and interactions among holons in the cooperation domains. Whereas the Sustainability Guidelines 6 to 9 of Table 1are used to complete the definition of the sustainability features and the Go-green Holons required in the system by means of completing details of the Interaction models and Agent models. The Environment Model is built in the fourth step, Specify Environment Relations, to represent non-autonomous domain entities with which the holons have to work.

STEP 4: Specify environment relations

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 have to analyze every holon in the current iteration in order to figure out whether it is convenient to decompose some of them. For every holon that it was decided would be decomposed a concurrent analysis process has to be applied in the next iteration. The requirement specification for every concurrent process is defined by the different models in the previous iteration, which specify the given holon. In this way, the incremental analysis steps define the integration rules and models developed in the different analysis processes. When there is no need for further decompositions (i.e. all the holons are "atomic") the system engineer 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 end up with the System Architecture completely specified. This phase is divided into two steps (Figure 5):

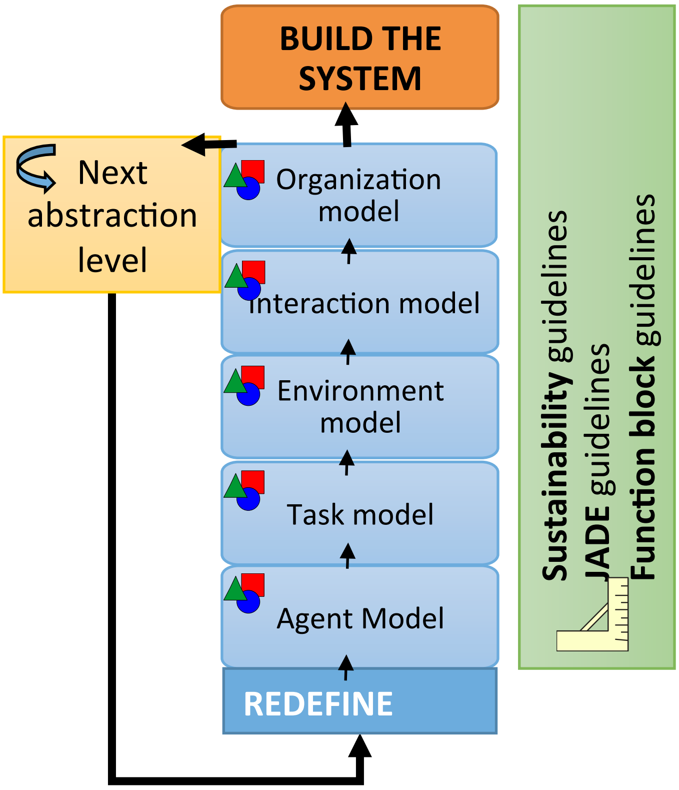

Figure 5: Design phase of Go-green ANEMONA

STEP 1: Refine Holon

This step's goal is to complete the analysis models without taking platform-modeling issues into account. The system engineer must focus on the "atomic" holons of the previous phase in order to complete their definitions. The Agent Model must be revised to include the internal execution states of the holon and 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 ensure that each agent goal has a corresponding task that pursues it. Pre and post conditions have to be identified for every modeled task. The Environment Model must be detailed to include the resource attributes and the agents' perceptions in terms of application events.

Once every atomic holon is completely specified, the system engineer must move up to the nearest abstraction level in the holarchy structure (from the Analysis Models), i.e., to the cooperation domain in which the given holon interacts. Dependencies among cooperation domains/holarchies are refined in the Organization Model. The Interaction Model is enhanced with preconditions, task executions and 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 there is no higher cooperation domain in the Analysis Models.

It is important to point out that Design Guideline 1 is supported by a decision flow diagram (Giret et al., 2015) that enforces researchers to explicit and to think about their main designs choices (a design choice being the choice of the best categories for each of the sustainable parameters taken into account in the SIMS) when designing a specific sustainable Go-green Holon. Let's imagine, for example, a situation in which a Go-green Holon is in charge of production scheduling, and the solution must take into account energy use, the number of machines, and CO2 emissions. At the same time, the scheduling must be achieved off-line, but must be adapted to react to run-time events such as machine breakdowns, new work orders entering the system, and variations in energy consumption. In addition, there are thresholds for makespan, energy use (peak power consumption, etc.), and CO2 emissions (quota). Finally, the makespan must be optimized, energy economized, and CO2 emissions reduced. The two last requirements will determine the way the multi-objective must be handled. For this concrete situation, it is required a solving approach that: takes into account energy and CO2; maintain the scheduling effectiveness as the main objective, while minimizing energy and CO2, and; is a proactive-reactive scheduling method (an initial schedule is computed off-line and re-scheduling activities are executed on-line). With this decision support the system engineer can chose from the library of pre-built solving approaches the one that better fits these requirements (see (Giret et al., 2015) for a list of approaches suitable for different sustainable requirements combinations).

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.

Table 2. Sustainability Guidelines of the Design Phase

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 platform. In the specialized literature there are many agent execution platforms that can be used and Go-green ANEMONA provides different sets of guidelines depending on the chosen platform. 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 work product 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 produced for each agent in the Design Models. A SIMBA Specification is built for every hard real time agent with no physical processing part. The Function Block Interface Specification is produced for the physical processing part of each agent representing physical processes, equipment or machines. The last Design Model is the UML Deployment Diagram. This 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

From the System Architecture the Holon Implementation phase produces the Executable Code for the SIMS. In this phase the programmers have to implement the information processing part of each holon and the physical processing part of each holon representing physical processes, equipment or machines. The Sustainability Guidelines 1 and 2 from Table 3 are specially tailored for helping the system engineer to implement the sustainable processes required by Go-green Holons. The Go-green ANEMONA CASE tool includes 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 IMS at the target destination. Finally in the Operation and Maintenance phase maintenance activities are performed. In the case of new requirements, a new development process must be initiated.

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.

Table 3. Sustainability Guidelines for the Implementation Phase

3.3 Development tools

The set of tools provided by Go-green ANEMONA comprises: 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; the set of prebuilt solving approaches from which the engineer can select the type of solving approach that better suites his/her needs for the efficiency-oriented objectives, constraints and KPIs (Key Performance Indicators).

This CASE tool is an extension of the EMFGormas CASE tool that can be downloaded at http://users.dsic.upv.es/grupos/ia/sma/tools/EMFGormas/. Figure 6 shows a snapshot of the tool where the main parts of the CASE tool are highlighted.

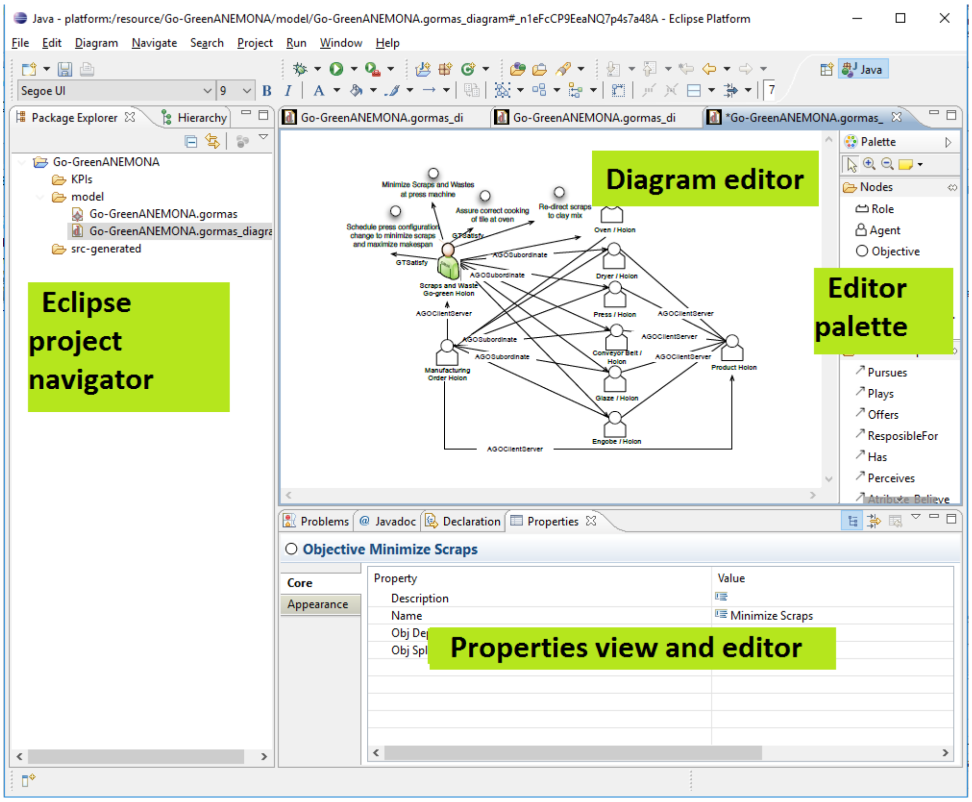

Figure 6: Snapshot of the Go-green ANEMONA CASE tool

4. Validation of Go-green ANEMONA

For illustration and proof of feasibility, two different applications are demonstrated and in-depth described: (i) A ceramic tile factory application in which the SIMS is tailored to: minimize scraps and waste of materials due to bad quality of the tiles; and minimize the energy consumption by re-using the oven residual heat in the drying stage of the production line. Apart from these goals the SIMS must also minimize the makespan. (ii) 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. Apart from these two applications, which demonstrate the feasibility of the method for developing applications from system conception until implementation, a third case study is presented to apply Go-green ANEMONA on an academic 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.

4.1 A ceramic tile factory Intelligent Manufacturing System

An intelligent distributed monitoring and control application of a ceramic tile factory is designed using Go-green ANEMONA. The sustainable goals to optimize in this application are: minimize scraps and waste of materials due to bad quality of the tiles; and minimize the energy consumption by re-using the oven residual heat in the drying stage of the production line. Apart from these goals the SIMS must also minimize the makespan. Figure 7 shows a diagram in which a Scraps and Waste Go-green Holon is designed with the goals: "minimize scraps and waste in the tile press machine", "assure a correct cooking of the tile", "re-direct tile scraps to the clay mix", "find-out the better production sequence of tiles' work-orders to minimize scraps due to press configuration changes". From the Sustainability Guideline for the Design Phase 1 (Table 2) the Scraps and Waste Go-green Holon uses an approach for scraps and waste minimization using a greedy randomized adaptive search (Escamilla et al., 2014) in order to find out the optimized sequence of work orders for minimizing scraps due to press configuration change. This approach is used in the Adjust Resource task in Figure 7.

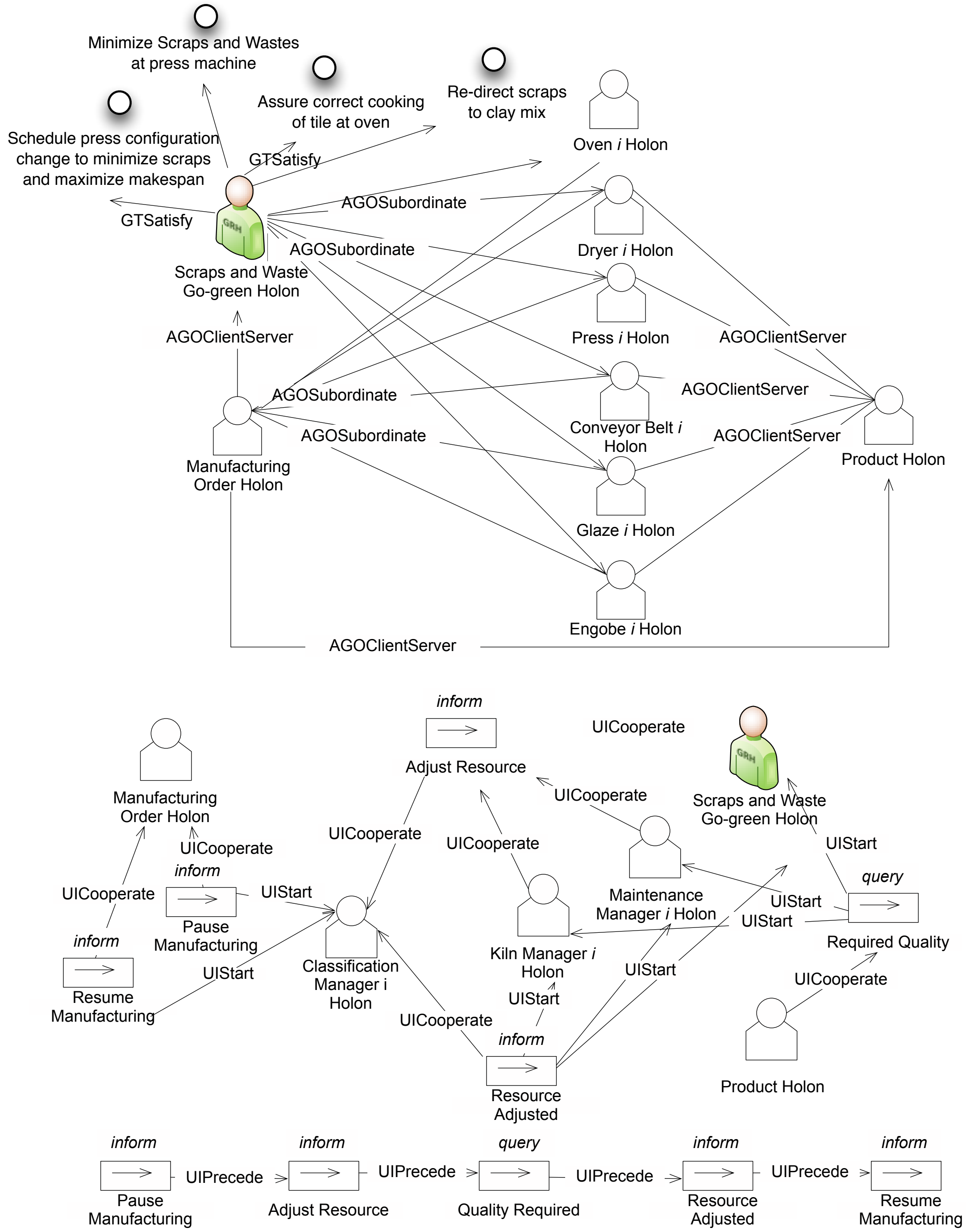

Fig. 7. Goals of the Scraps and Waste Go-green Holon, its relations with classical holons, and a cooperation diagram for controlling a tile pressing, painting, cooking and quality classification line

4.1.1 Discussion and lessons learned

The goal of this case study was 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 SIMSs each for the ceramic tile factory case study. One team used Go-green ANEMONA, and the other developed the SIMS using ANEMONA without the specific guidelines and without the Go-green Holons. Table 4 shows the gaining using 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

Table 4: Case study comparison: ANEMONA vs. Go-green ANENOMA

From Table 4 it can be noticed that the number of iterations to find out the set of holons that implements the SIMS are the same, but in terms of duration Go-green ANEMONA outperforms ANEMONA by 0,5 months. For measuring the Easy to Design and the Guidelines Usefulness it was used MASEV (Garcia et al., 2011) (a MAS evaluation framework). This framework allows analyzing and comparing methods and tools for developing MAS in terms of general requirements, and the method guidelines provided. The analysis is a questionnaire in which the system engineers answer different questions related with the aspect that is being evaluated, and provides a numerical value with respect to the given answer. It can be noticed that Go-green ANEMONA got 9,5 out of 10 when evaluating the usefulness of Go-green Holons

(Easy to Design).

Whereas a 9,2 out of 10 when evaluating the usefulness of the specific guidelines for designing SIMS. On the other hand, when evaluating the Number of Holons identified with Go-green ANEMONA it turns out that 8 more holons were identified compared with the ANEMONA development. This is because the Go-green Holons are added to the classical holons in the development. But the Go-green Holons have helped to have less cooperation domains with Go-green ANEMONA since there is no need to have dedicated cooperation domains for sustainability issues since there are already taken into account in the different cooperation domains in which the Go-green Holons are involved. Gaining in this way in terms of cooperation domain configuration, initialization, execution and deletion.

From this particular experiment we can conclude that Go-green ANEMONA facilitates 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).

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

In this case study, one of the most widespread manufacturing industry, plastic production by injection molding, which is also one of the greatest industrial energy consumer (2.06 108 GJ per year only in USA) is considered. The faced problem consists in scheduling off-line a set of orders on a set of parallel injection molding presses, where a product type characterizes each order and a penalty cost for late delivery. A set of alternative presses is available for each order and both the processing time and the energy consumption depend on the order-machine pair. Since mold change and cleaning are required between two successive operations on the same injection press, also setup times must be considered. Accordingly, the examined case is a multi-objective scheduling problem in which the total tardiness, total setup time and total energy consumption must be minimized.

In this particular case study Go-green ANEMONA is used in order to design a MAS model for solving the above-described 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 committed to solve a partial problem by scheduling all jobs assigned to the individual machine the holon is responsible to manage. The Go-green Scheduler Holons receive their partial problems and use a mixed integer programming (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 due to the fact that all jobs have been distributed and thus the energy consumption of each job is assigned. This issue is fundamental for the MAS model 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.

Figure 8 depicts the interaction sequence among the holons. The list of exchanged message and their sequence are overviewed in this figure. The vertical line (from each holon) in the diagram represents time and the execution thread of each holon. An arrow between two holons represents a message passing from one holon to the other (i.e. the sending holon is requesting the execution of a given function from the receiving holon, or the sending holon is informing the receiving holon a given data).

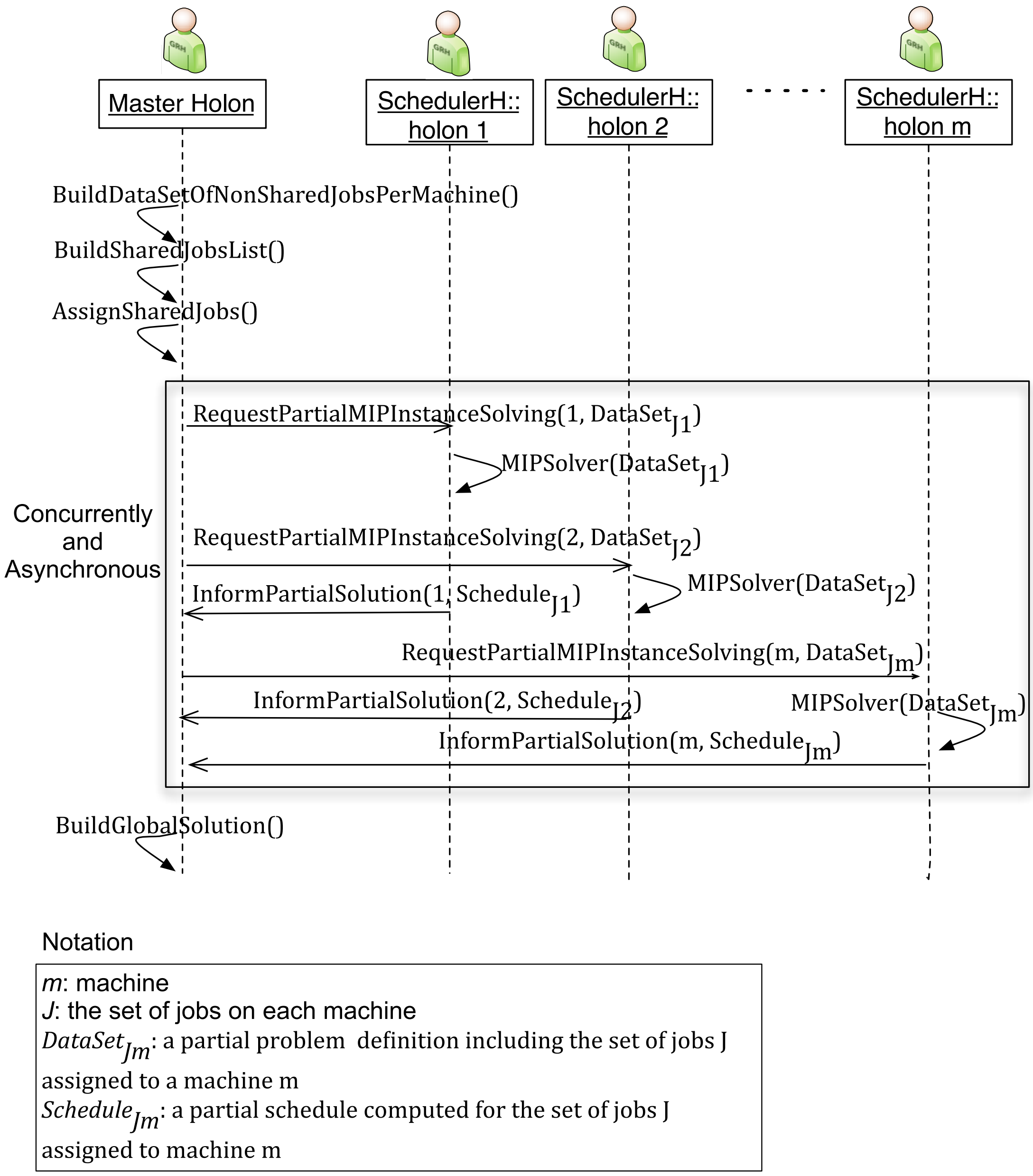

Figure 8: Interaction sequence to solve the distributed scheduling problem

4.2.1 Discussion and lessons learned

The goal of this case study was to assess the quality of the solution derived with Go-green ANEMONA. To this end the MAS distributed solver was compared with a centralized approach (based on MIP) that solves the same scheduling problem. The evaluation was done through simulation comparing the two solvers in order to assess their efficiency, scalability and solution quality (Tonelli et al., 2016).

Figure 9 shows the results of the evaluation. The details of these figures are presented in (Tonelli et al., 2016), whereas in Figure 9 the percentage variation of the different objectives (tardiness, setup time and energy consumption) of the MAS model against the MIP approach are summarized by a bars chart. 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. All instances were run for MIP and MAS models on a 2.4 GHz Intel Core 2 Duo with a 3600 seconds timeout. The MAS model was able to obtain a better behavior in total tardiness and energy consumption in almost all instances, whereas the MIP model returned better values for the setup times. This is due to the fact that 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 any case, the improvement is mainly significant in tardiness values.

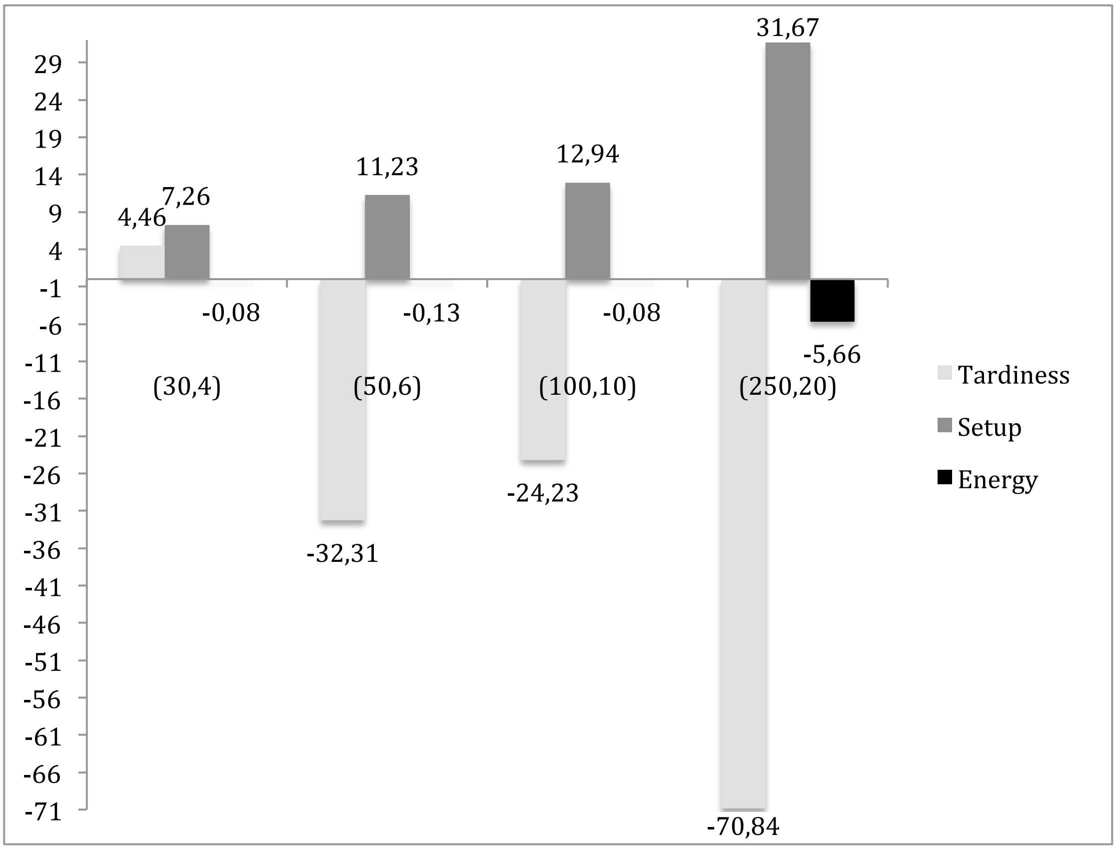

Figure 9. Percentage variation of Average Tardiness, Setup time and Energy consumption in the different classes of instances

4.3 Adding sustainability value to an energy-aware Flexible Manufacturing System

The feasibility of Go-green ANEMONA being illustrated, our aim is to implement this method on a real manufacturing system and to show its benefits towards sustainability compared to a previously implemented manufacturing control approach dealing with a specific and important aspect of sustainable manufacturing which is energy.

The FMS used in this case study 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.

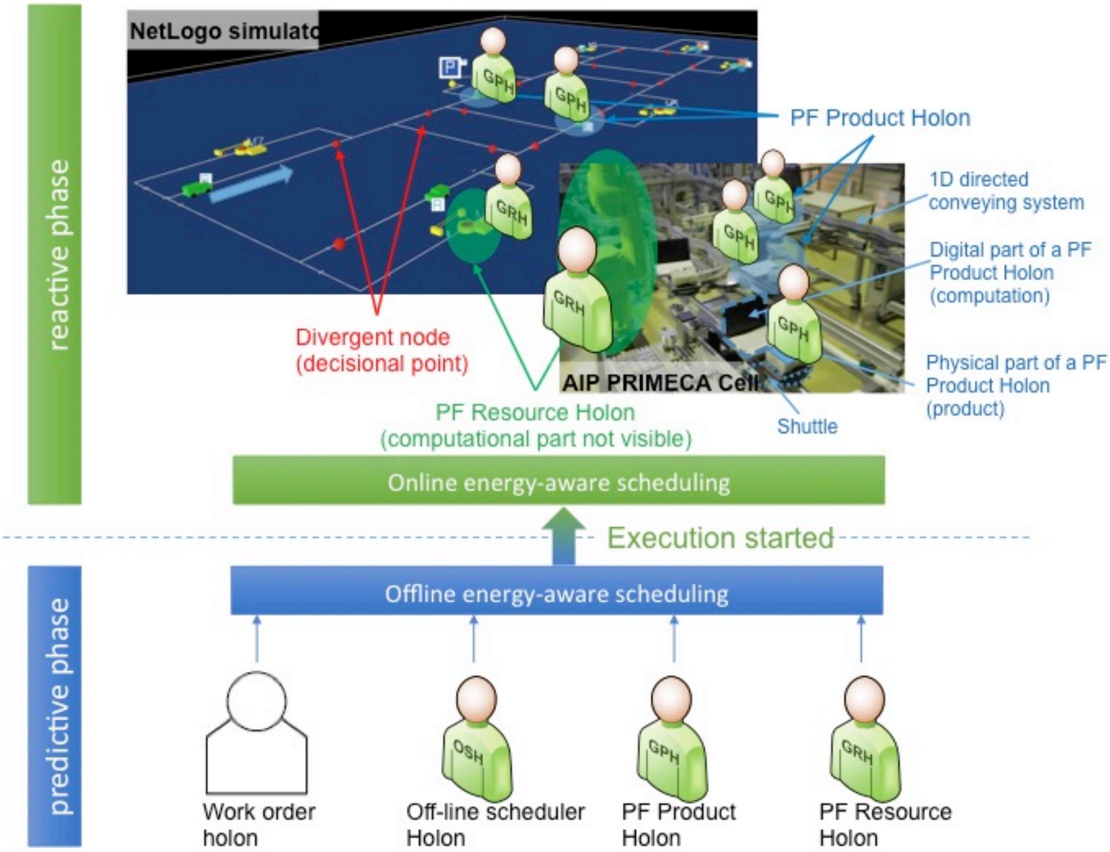

Figure 10. Hybrid FMS distributed model derived with Go-Green ANEMONA (Netlogo simulator and corresponding AIP PRIMECA cell "proof-of-concept" implementation).

Go-Green ANEMONA is here 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. Figure 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 the energy consumption maintaining the hard constraint of their local energy threshold.

Figure 11 depicts the interaction diagram of the proposed distributed problem solving. It is divided in two phases: an offline/predicting scheduling and an online/reactive scheduling. In the first phase, an initial energy-aware schedule is solved, 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 maintain 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:

$$minimize(Makespan, EnergyConsumption)\ s.t\ (Makespan < Threshold_{Makespan}\ And\ EnergyConsumption < ThresholdEnergy). \quad (1)$$

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.

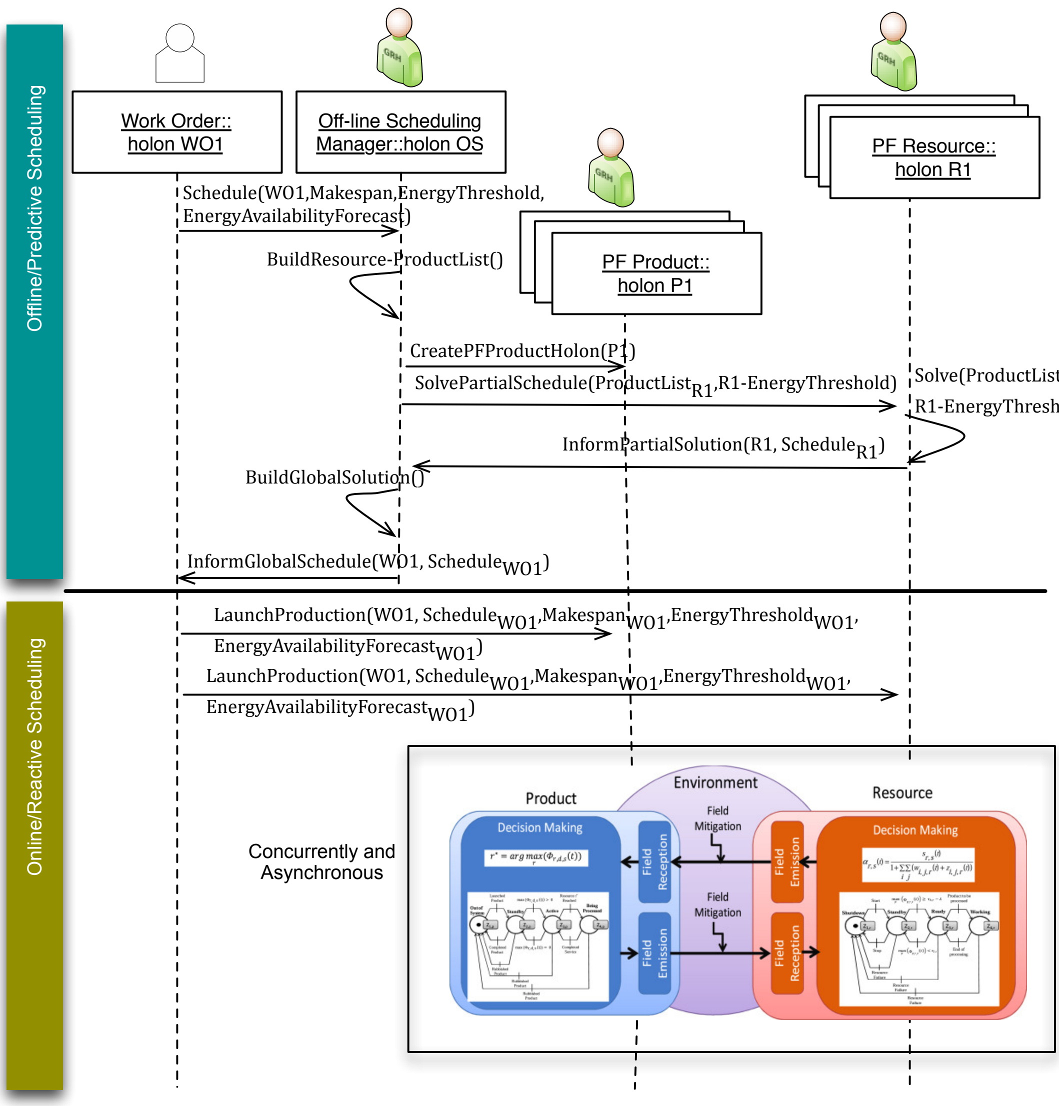

Figure 11: Interaction diagram for a hybrid energy-aware FMS model.

4.3.1 Discussion and lessons learned

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

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 are the needs to integrate sustainability efficiency performance in IMS design? 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: how can these needs be approached using concepts from IMS engineering methods in the context of design of sustainable manufacturing systems? was treated. We answered this last question proposing a concrete software engineering method that helps developers to develop sustainable intelligent manufacturing systems. 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, 2015a) that fosters system designers to achieve sustainability features into manufacturing operations control architectures. Go-green ANEMONA provides the methodological benefits of holons and multi-agent systems for the identification and specification of sustainability specific features of manufacturing systems. It is focused on 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 are seeking to have manufacturing specific guidelines and sustainability specific analysis/design activities and constructs for developing sustainable manufacturing operations architectures. The method enforces system engineers to explicit and to think about their main designs choices of the sustainable parameters taken into account in the SIMS.

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 from which the engineer can select the type of service that better suites his/her needs for the efficiency-oriented objectives, constraints and KPIs of go-green holons is being extended. 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.

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