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# A dynamic hybrid control architecture for sustainable manufacturing control

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**Abstract:** Manufacturing systems face the challenge of accomplishing the productive effectiveness and sustainable efficiency goals at operational level. For this, manufacturing control systems must incorporate a mechanism that balances the trade-off between effectiveness and efficiency in perturbed scenarios. This paper proposes a framework of a dynamic hybrid control that manages and balances the trade-off between effectiveness and efficiency objectives. Our proposal integrates this trade-off in three different locations: the predictive-offline scheduling component, the reactive-online control component, and the switching mechanism that changes dynamic architecture. To show the contribution of our approach and the progress of our research, a case study dealing with energy-aware manufacturing control is presented.



***Keywords: Intelligent Systems, manufacturing Control, Sustainability, Energy-aware scheduling, manufacturing control system.***

## 1. INTRODUCTION

Sustainability in manufacturing has gained interest in both academic and industry fields as an opportunity to improve the effectiveness (completion of objectives) and efficiency (use of resources) in enterprises operations. Some benefits for embedding sustainability in enterprises are the mitigation of operational risk and reduction of wasting in the consumption of limited resources as energy, materials, etc. (Laszlo and Zhexembayeva 2011). From a global perspective, the concept of sustainable manufacturing suggests developing practices in manufacturing that ensure a sustainable evolvement in the social, economic and environmental dimensions (Stock and Seliger 2016). It involves the creation of manufactured products from processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound (Rosen and Kishawy 2012). The design of sustainable manufacturing operations must include mechanisms that fulfil these goals simultaneously to reach the efficiency and effectiveness desired. However, in the implementation phase, the difficulty of maintaining sustainable practices lies in the fact that social and environmental goals are often conflicting with the economic ones (Montoya-Torres 2015). In this sense, the challenges of sustainable manufacturing are to include properly the social, environmental and economic goals in the decision-making of manufacturing operations, and create an appropriate method to reach a proper trade-off. Still, it is noticed that the integration of sustainable metrics in real-time scheduling clearly represents a significant challenge (Fang et al. 2011).

Since the last decade, researchers have included sustainable concepts at lower manufacturing levels (Garetti and Taisch 2012; Herrmann et al. 2014; Prabhu et al. 2015). Nevertheless, from a preliminary review, very few studies have focused on the inclusion of sustainable concepts in the manufacturing control domain. We define a sustainable manufacturing control system as the interconnection of heterogeneous hardware/software components (e.g. products, machines, sensors/actuators, optimization packages, etc.) that are synchronized and integrated into an architecture to monitor, manage and influence the behaviour of a manufacturing system in a way that pursues conjointly the achievement of social, economic and environmental goals expressed in terms of effectiveness ("doing the right things") and efficiency ("doing things right").

The inclusion of sustainability principles in the manufacturing control activity is highly complex. In this paper, the focus is set specifically on two issues. The first one is related to the fact that effectiveness and efficiency are naturally conflicting objectives. The second issue concerns the need to perform an online evaluation of the sustainability metrics to make short-term decisions paying attention to a longer time window. Addressing these two issues, our contribution is related to the creation of control mechanisms that perform a proper trade-off between effectiveness and efficiency metrics, both at a short-term (reactivity) and a long-term time window (overall optimization).

From our point of view, and among the set of possible approaches to design control architectures, the concept of *dynamic hybrid control architectures* (D-HCA) seems to be an effective reference approach. The concept of hybrid control


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architecture, aiming to deal simultaneously with short-term reactivity and long term optimization is not new (Nakhaeinia et al. 2011; Arkin 1998; Murphy 2000). The integration of dynamic features addressing the evolution of the architecture itself is more recent and refers to the ability to reconfigure the architecture according to events. In the domain of embedded systems and computer sciences, this aspect is often dealt and authors often use the term “Reconfigurable control architectures” for this kind of hybrid control architectures. In the manufacturing area, the use of this term is not well standardized but a lot of works are made relatively. Let us mention for example ADACOR (Leitão and Restivo 2006), PROSA (Van Brussel et al. 1998), ORCA (Pach et al. 2014) and POLLUX (Jimenez et al. 2016) that are clear examples of D-HCA. In manufacturing, the main characteristics of a D-HCA are: First, a D-HCA is a dynamic composition of two or more automated entities that couple predictive/offline and reactive/online techniques to schedule and respond properly to unexpected events. Second, a D-HCA can switch dynamically its architecture and coupling level either for improving its performance or responding to perturbations. And third, a D-HCA permits the particularization of performance metrics in the decision-making process to trigger the switching between structures and generate balanced multi-criteria mechanisms not only for local but also for global decisions. Despite these benefits, it has been shown that very few contributions in the D-HCA domain (and more globally, in the manufacturing control domain) have been proposed to handle sustainability principles (Giret et al. 2015). Some attempts are being made at a methodological point of view (Giret and Trentesaux 2016) and most of the existing works in manufacturing control focus specifically on one of the drivers for sustainability which is energy. For instance, Mouzon et al. (2007) minimize the energy consumption and the total completion time presenting a method that couples a MILP/dispatching-rules architecture for the scheduling in a manufacturing facility. In another example, Klopper et al. (2014) integrate the energy consumption with the makespan, maximum tardiness and the average tardiness metrics in a coupled multi-objective task planner and greedy-assignment heuristic. Also, Zhang et al. (2013) integrate a makespan and energy consumption in a coupled goal programming and a genetic-algorithm method.

In such a context, the aim of this paper is to propose a sustainable D-HCA system that integrates the sustainability metrics within the manufacturing execution level. An example in the domain of energy-aware scheduling is proposed. The paper is organized as follows: our proposal is presented in section 2. Its implementation dealing with energy aware scheduling is presented in section 3. Section 4 presents the experimental results and the conclusion and future perspectives are given in section 5.

## 2. SUSTAINABLE POLLUX

This section presents ***Sustainable Pollux*** as a sustainable D-HCA. This proposal is an extension of a previously developed approach named Pollux where the concept of Go-Green manufacturing holons is suggested to be integrated to cope with sustainability objectives. *Pollux* was initially an adaptive and evolutionary D-HCA that searches dynamically for an optimal coupling between predictive (e.g. offline scheduling) and a reactive (e.g. online scheduling) techniques in hybrid control architectures (Jimenez et al. 2016). *Go-green manufacturing holons* (see fig. 1) are autonomous and cooperative holons that represents physical manufacturing entities (i.e., products, machines, conveyors, AGV, etc.), whose decisions are balanced through a trade-off between efficiency-oriented and effectiveness-oriented indicators required to undertake activities in sustainable manufacturing objectives (Trentesaux and Giret 2015).

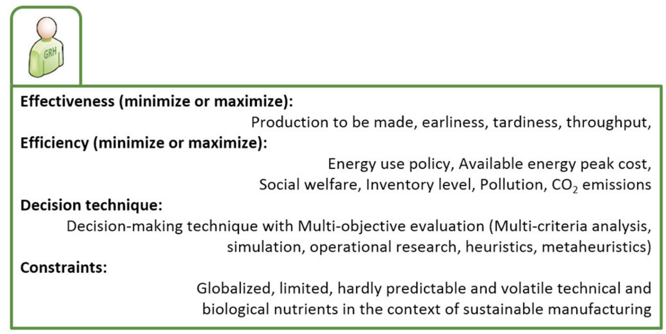


**Fig. 1** Go-green manufacturing holon (Trentesaux and Giret 2015)

***Sustainable Pollux*** is organized in two separate subsystems: a *Control system architecture (CSA)*, which is composed of a set of go-green manufacturing holons that represents the architecture of the control system, and a *switching mechanism (SM)*, which function is to monitor the system performance, and, based on it, is in charge of changing the operating mode of the CSA when necessary. An operating mode is defined as a specific parameterization (definition of all parameters) of the CSA that characterizes the functioning settings of the control system. With these extensions, Sustainable Pollux implements the go-green manufacturing holons into the initial Pollux approach and extends the objectives of the switching mechanism to handle sustainability within the system monitoring and operating mode switching. More precisely, Sustainable Pollux is organized as follows:

Control system architecture (CSA): the CSA is organized using two coupled layers: a global and a local layer. The **Global layer** hosts a global decisional entity (GDE), which is modelled as a Go-green manufacturing Holon and provides the predictive/offline elements, being planning, scheduling, dispatching, routing and energy management (denoted sustainable-GDE or **sGDE**). The **Local layer** hosts the sustainable local holonic decisional entities (e.g. sustainable-LDE or **sLDE**) and sustainable holonic resources decisional entities (e.g. sustainable-RDE or **sRDE**), which are also modelled as Go-green manufacturing holons. Each sLDE, which represents the jobs associated with each production order, is responsible for the managing of the job behaviour based on a reactive/online control approach. Each sRDE, which represents the machines, handles the processing activities based on a service-oriented approach. Aside from the decision-making technique (either predictive or reactive approaches), the sustainability metrics are integrated into the settings of the effectiveness and efficiency indicators of each decisional entity (sGDE, sLDE and sRDE). While some examples of effectiveness goals are the optimization of the makespan, throughput or order tardiness, examples of