Emerging key requirements for future energy-aware production scheduling systems: a multi-agent and holonic perspective

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Abstract. The aim of this paper is to study a set of emerging key-enabling requirements for the design of multi-agent or holonic manufacturing systems dealing with the energy aware scheduling of future production systems. These requirements are organized according to three different views, namely informational, organizational and lifecycle views. It is shown that these emerging key-enabling requirements are not sufficiently addressed by the literature. An illustrative futuristic example of a system complying with these requirements is provided. From this example, new research opportunities and issues can be easily found.

Keywords: energy aware scheduling, intelligent manufacturing systems, multi-agent systems, holonic systems, requirements.

1 Introduction

This paper focuses on the challenging issue of energy aware production scheduling. Energy aware production activities are nowadays and will remain in the future a major industrial issue because of the increasing short-term volatility in cost and availability of energy coupled to an increasing average (long-term) cost of energy.

This paper lies within the field of Intelligent Manufacturing Systems (IMS). In that field, one can face an important set of contributions dealing typically with the design of multi-agent systems (MAS) and holonic manufacturing systems (HMS) to control in a predictive or reactive way the scheduling of manufacturing activities. Among this abundant literature, energy starts to be considered in the development of energy-aware MAS and HMS [1] in response to the challenging issue introduced. One main advantage of using IMS based approaches such as MAS and HMS in energy-aware production comes from their potential ability to cope with the unexpected and the complexity induced by the energy-dimension [2].

Meanwhile, designing energy-aware production scheduling systems (EAPS²) requires a set of profound modifications not only in MAS/HMS scheduling control models but also in informational and organizational processes in industry to exploit or permit the use of these MAS/HMS based EAPS². In other words, focusing only on the core activity of scheduling with no attention paid to key-enabling energy-compliant requirements is a too restrictive view: a more global view is required, where the EAPS² is immerged in a more global environment enabling its functioning [3]. In that sense, this paper is aligned with the conclusion of an interesting study [4] pointing out the gap between research and industry in energy management in production and fostering researchers to work on: the design of energy-aware decision support systems to visualize and handle trade-offs between energy and other KPIs; to realize full benchmarking activities; to develop improved monitoring and control systems of energy; and, to extend MES and ERP to support the energy as a new clear dimension.

In this context, this paper intends to study key-enabling emerging energy-requirements of MAS/HMS based EAPS² that enable a viable integration of the designed MAS/HMS based EAPS² in next generation production environments. We assume then that the EAPS² is designed using IMS principles, the introduced expected advantages of MAS/HMS paradigm in the context of energy management being considered. Meanwhile, it is important to note that this paper does not focus on energy generation issue and does not deal with the internal design of the EAPS² itself neither, for which several literature reviews and a large amount of work are available [5].

2 Key-enabling emerging requirements in MAS/HMS based energy-aware production scheduling

The impact of the design of energy aware processes in future factories has been studied in recent years [6]. Inspired from [7] and aligned with the conclusions presented in [4], we study here several key-enabling emerging requirements that we classified in three categories, namely informational, organizational, and life cycle points of view:

- Informational point of view:
  - REQ#I1: A MAS/HMS based EAPS² must be interoperable with other information systems of the enterprise or beyond,
  - REQ#I2: A MAS/HMS based EAPS² must be able to observe and control energy variables of energy consuming resources.
- Organizational point of view:
  - REQ#O1: A MAS/HMS based EAPS² must be able to control the different types of energy wastes that have been identified and categorized,

- REQ#O2: A MAS/HMS based EAPS² must be able to support reconfigurations of the manufacturing systems, according to the cost and the availability of energy in the mid-long term as well as manufacturing resources availability.
- Life cycle points of view:
  - REQ#L1: like any system designed according to sustainability principles, the lifecycle assessment of a MAS/HMS based EAPS² must be done.

As introduced, these requirements are emerging key-enablers. In other words, they are pre-requites to design viable MAS/HMS based EAPS² in a near future context where the availability of energy as well as its cost will be more and unpredictable. It is important to note that this context will not evolve in a favorable way: the long-term average energy cost, still increasing coupled with the reduction of fossil-based energy availability will force industrialists to consider alternative integrated energy sources (wind, solar energy) that will contribute to increase further this unpredictability in availability and cost of energy purchased and produced.

It is clear that these key-enabling emerging requirements are not proved to be exhaustive, but from our point of view these are among the critical ones. In the remaining of the paper, these key-enabling emerging requirements are detailed and discussed. When available, illustrative examples from the literature are provided.

3 Integration of these key-enabling emerging requirements in MAS/HMS based energy-aware production scheduling

3.1 REQ#I1: interoperability with information systems

There are different information systems the MAS/HMS based EAPS² must be at least interoperable with one enterprise's information system application layers dealing with production, mainly ERP (Enterprise Resource Planning), APS (Advanced Planning and Scheduling), MES (Manufacturing Execution Systems) and SCADA (Supervisory Control And Data Acquisition) systems. The interaction with these systems occur at a transactional level (ERP, MES, SCADA) as well as at a simulated off-line level (APS); this last interaction improves convergence between ERP and MES by allowing "what-if" scenario generation and analysis and where EAPS² can be an important component. Often neglected, the impact of all the emerging requirements to a manufacturing system when seen through a sustainability point of view is profound. It is causing shifts in the way manufacturing companies operate, interact with their customers (especially other businesses), and offer services and products. In fact, almost every aspect of a business will be affected by a comprehensive global sustainability approach. In order to provide solutions to this situation, enterprise level management modules are starting to be conceived as tools in which energy and sustainability needs are intertwined (an example is ERP Green from Sustainable Dynamics). This requirement drives attention to the impact of the right interoperability between information systems and a MAS/HMS based EAPS² in order to implement a holistic sustainable approach, unless parts of the "global chains" are broken. It is crucial that the information that flows among the different levels of the global environment in which the EAPS² is immersed is properly taken into account.

The upper management levels (typically, ERP/APS) are key for the right functioning of EAPS², being MAS/HMS based or not. The information that comes from, for example, an ERP defines the activating events for an EAPS² in order to start a new schedule or to dynamically react modifying a running one through for example the interaction with a supervisory or staff holon (PROSA-like approach). Not only the incoming information is key, but also the outgoing information that must flow timely and with the right format to the upper management levels in order to assure the optimized treatment of the means by the global manufacturing system and to provide energy-oriented (and more, globally, sustainability oriented) relevant information to decision makers. Furthermore, such integration will pave the way to "information platforms" that visualize the means of the factory on different levels taking into account new kinds of Key Performance Indicators (KPI). These KPIs should also be used for benchmarking or even for efficiency labels for factories, processes, machines and products.

Research works that explicitly tackle this requirement are still lacking, despite the fact that it was already identified in the Strategic Research Agenda ranked list from the REViSITE project ICT4EE roadmap [8]. From an industrial point of view, some companies in the ERP-sector have already launched initiatives to include analyses on resource and energy efficiency as well as carbon emissions in their software, but this is not sufficient [4].

At a lower management levels, the link with MES and SCADA systems is also to be studied in a holistic way. Holonic Manufacturing Execution Systems (HMES) could be for example extended in the context of EAPS² using for example the concept of go-green holon [9] to enable the monitoring of energy-based KPI (cf. REQ#I2).

Meanwhile, this "vertical" interoperability is not sufficient and must be completed by "horizontal" interoperability, the one that deal with product and systems life cycle management (eg., Product Lifecycle Management PLM software). From our point of view, the concept of "intelligent products" [10] can be adapted in the context of energy-aware lifecycle management for example.

More, even this widening is not sufficient. Indeed, some innovative interoperability links can be identified when considering that the MAS/HMS based EAPS² should also be interoperable with systems beyond the enterprise itself, and among them, the energy provider systems. This interoperability will concern the gathering of *reliable* information about energy peaks, availability, and costs, but will also concern possible negotiation with these systems to find a compromise between production needs and energy offers, as it will be illustrated in the example provided at the end of the paper.

3.2 REQ#I2: ability to observe and control energy variables

From a software point of view, the capability to collect and to manage energy consumption information at the desired granularity (from sensors/actuators level to business management level) is needed to identify demand patterns and to develop appropriate strategies and policies to address energy management and saving opportunities.

Also, the capability to measure detailed energy utilization insights into sub-system interactions can lead to further efficiency improvements as much as the interactions are comprised and modeled. From a hardware point of view, energy-aware sensors and actuators need to occur simultaneously to allow for such pervasive monitoring and energy control. Moreover, standards for the design and deployment of optimal sensor networks as well as "smart" energy devices are required for the integration with higher-level energy management systems (see for instance IEC/TR 62837 Energy efficiency through automation systems). This requirement bridges then the digital world with the physical one. Within the context of MAS/HMS based EAPS², controllability and observability logically lead to the integration of the concept of "cyber-physical systems" (CPS) when defining the EAPS².

A MAS/HMS based EAPS² requires such a CPS approach to enable it to "close the loop", from energy sensors to actuators through control decisions. This requirement refers to the well-known concepts of "controllability" and "observability" of systems from the control theory:

- *energy controllability* ensures that the decisions of the MAS/HMS based EAPS² *actually* influence energy-related KPIs. This is often the case but some basic attention must be paid to avoid uncontrollability (eg., if a holon controls the speed of a robot for which the energy used per time unit is inversely proportional to this speed, then the total energy consumption for this robot is unfortunately uncontrollable by the holon).
- *Energy observability* requires that energy-consuming resources (in a broad sense) must be equipped with technological solutions enabling the real-time measurement and the forecasting of:
  - manufacturing energy supply or needs;
  - resources energy consumption;
  - peak overall power consumption during manufacturing;
  - energy prices and energy costs for manufacturing;
  - re-used/recycled energy wastes (cf. REQ#O1),
  - energy efficiency measures and related performance indicators.

The energy consumption remains hard to measure and to model, then hard to predict. Typically, consumption depends on a lot of various parameters depending on low level physical processes, operations, product characteristics (weights), age of resources, maintenance, etc. In [11], authors propose a standard-based infrastructure to collect and monitor energy data in real time for manufacturing and production systems, along with a manufacturing energy management system (MEMS). In case of difficulties to measure energy directly, control theory and modern identification technics (observers and state re-constructors) can be used and embedded into holons. Other technics, such as function blocks approaches, discrete event modeling and simulation, axiomatic or feature-based design may also help to measure indirectly energy and to predict its evolution [12]. Meanwhile, in the context of IMS and from our review, existing energy profile models embedded into holons remains very (too) simple. For example, in [9], a MAS/HMS based EAPS² was applied on a flexible manufacturing system for which direct resource consumption was not measurable in real-time.

To solve this issue, a highly simplified energy consumption model has been designed from offline single tests with global measurements at the cell level. From these essays, a three constant levels consumption model has been chosen for each of the robot controlled by a holon (robot off mode: consumption 0, in sleeping mode where power was not supplied to the robot: constant consumption C_1, and working mode: constant consumption C_2). This kind of model is clearly not sufficient since: the consumption depends in fact on the load of robots; the peak/Dirac consumption at starting moments of movements was always neglected; etc. More elaborated energy models have been developed in [13]. In this work, each production resource is associated with an intelligent agent providing the interface with information systems (e.g., APS, MES…). 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 KPI such as energy used per operation type, total consumption, etc. The global architecture of this MAS/HMS based EAPS² enables to support dynamically and in an easier manner changes in the physical world providing an additional improvement for decision-support tool for performance measurement and management in the industrial sustainability and sustainable supply chains domain [14]. But as for the previous example, observers consider the observed system as a black box to be identified according to classical control theory approaches.

In fact, controllability and observability difficulties come from the situation when resources have not been designed to support energy measurement and control. Nowadays, recent machines and robots are being equipped with "energy modules". Meanwhile, a great majority of existing resources are still not equipped while for some of them, cost issues or contextual constraints (corrosive environment, etc.) forbid and will still forbid such an equipment.

Finally, it is important to note that all the previous discussion deals with energy expressed in term of electric power. This holds also true for the literature. Meanwhile, other kinds of energy sources can be found, for example energy from air compressors. Even if the primary energy is electricity to generate compressed air, the actual use of compressed air is complicated to express in terms of energy use. In the previously cited example [9], the conveying system use both electrical energy (for shuttle moves) and air (for switching gates). The measurement of the conveying system energy consumption was then so hard to realize that the authors of this MAS/HMS based EAPS² neglected this consumption.

3.3 REQ#O1: ability to control the different types of energy wastes

This requirement deals with organizational issues since it requires the revision of industrial processes and production methods themselves to integrate lost energy harvesting and re-injection systems. It is important to note that energy wastes make the energy use efficiency decrease (and for some industries, the amount of waste is of the same order of magnitude than the energy used to add value to products). The idea is to recycle energy wastes as possible "free" energy input in the production system and to offer the MAS/HMS based EAPS² opportunities to reuse these wastes (by defining holon managing these wastes). More, this provides a new decisional criterion for holons when controlling production since they must also consider the minimization of the part of the wasted energy that cannot be harvested and that will be definitely lost. This kind of requirement concerns for example chemical/process industries or high energy consuming manufacturing systems like plastic production by injection molding or manufacturing systems with heat treatments. In such industries, energy waste generated from heat losses during machining can be considered as a potential non-negligible "free" input energy to be handled.

Meanwhile, despite the fact that this original requirement can be seen as a source of important savings, from our knowledge, there is no MAS/HMS based EAPS² paying attention to it. One reason comes from the fact that only few industrialists have mature solution to gather energy losses. From our point of view, the coupling of the global monozukuri design principle from the Japanese automotive industry with HMS/MAS based EAPS² could be an interesting evolution. Also, inspiration can come from other domains: building engineering, embedded systems and transportation of energy in the grid.

3.4 REQ#O2: ability to support reconfigurations of the manufacturing systems

MAS/HMS based EAPS² must be able to support reconfigurations of the manufacturing system. Reconfiguration is here understood in its broad sense, according to different conditions (long-, mid-, and short-term) aligned with the management of energy at the same long-, mid-, and short-terms.

The long-term reconfiguration is related to the factory life-cycle and involves lifecycle engineering and product/process revisions in order to reduce energy consumption in terms of material, transformation, processing of raw materials, components, and final products or alternative ways to supply energy to the factory being using integrated renewable resources or acquiring energy somewhere else. The long-term reconfiguration can also include new designed or purchased equipments with energy efficiency increased capability. In this case the MAS/HMS based EAPS² should transform existing energy requirements into the new reconfigured resource and constraints networked layout. As a consequence and to support long term reconfiguration, a holonic control architecture must be reconfigurable (ie., adaptable, evolvable) as well, following the different configurations of resources. This kind of reconfiguration is closely related to the REQ#L1 detailed hereinafter.

The mid-term reconfiguration, typically addressed at planning level, try to recombine existing resources in what-if planned scenarios (the typical domain of APS systems) by using aggregate data on resources availability and production constraints (being energy one of these) with respect to some cost or target function. In this case the MAS/HMS based EAPS² should be capable to elaborate feasible solutions, accordingly to contextual decision variables and decision maker's preferences, and showing the impact of them in terms of energy and cross-functional KPIs [15]. This can be done typically through cooperation or negotiation mechanisms among holons or agents. The obtained results can then be deployed to local areas, plants, lines subject to the interoperability requirement (see REQ#I1).

The short-term reconfiguration involves scheduling (and hence optimization where possible) of improved sequences flattening energy peaks, reducing total energy demand in a given time frame (day, shift, hour), selecting alternative resources in order to maximize energy saving, up to real-time monitoring and control of equipment and machines, providing switching on/off, stand-by and other sensor-actuator policies [16]. This kind of reconfiguration is the most addressed in the literature since it is the closest to the scheduling issue [17].

3.5 REQ#L1: lifecycle assessment of MAS/HMS based EAPS²

In conjunction with the previously introduced long-term reconfiguration ability and in addition to the improving of current operations, consideration must also be given to the performance of future systems and equipment. For this, Life Cycle Assessment (LCA), which uses historical data, must be communicated to system and equipment designers alike. This data will permit designers to develop systems that can be more easily adjusted to reduce peak energy requirements and to provide overall gains in average consumption from past experiences. Furthermore, designers will not only have a better knowledge of expected energy efficiency, but also will be able to better model and design the system to achieve even greater savings. Effective Life Cycle Engineering (LCE) analysis, for instance, requires a holistic analysis of product design as well as process design in order to allow energy awareness in the manufacturing phase, providing key features not only at product level but at equipment and machines level, specifying requirements in terms of energy metering, saving, and controlling phases.

Accordingly to this extended view of factory life-cycle, a MAS/HMS based EAPS² should support the capability to integrate advances in technology allowing for example long-term product/process reconfiguration (REQ#O2); this opportunity may only occur occasionally so when it arises, efforts must be made to incorporate all existing knowledge into the design of higher efficiency systems and equipment. Typically, a holonic architecture complying with this requirement must be designed to support different technology modellings in a generic way (eg., libraries).

A MAS/HMS based EAPS² is also a software product, which is designed to operate in an environment in order to achieve a set of goals. In order to assure its correct and efficient execution performance-monitoring activities must be performed. The key to any system’s effectiveness is whether its operations and outputs are achieving the performance targets. For a MAS/HMS based EAPS² this is directly linked to its environment and its set of goals, considering at the same time the changes that these elements may experience during the life cycle of the global manufacturing system. The environment in which the MAS/HMS based EAPS² exist is outlined by the definition of the different levels of the manufacturing company in which it is running, and the manufacturing processes that are scheduled in order to produce products. On the other hand, the set of goals that must be achieved by the MAS/HMS based EAPS² is normally defined as a set of multi-objective criteria that can include: classical time-based (completion times, flow times, tardiness/earliness…), or mixed time/quantity-based (throughput…) production objectives, together with sustainability means such as energy, CO_2 emission, waste, scrap, pollution, etc.[5], [18]. As a consequence any change or new requirement on any of these elements will affect the performance of the MAS/HMS based EAPS². The majority of works on designing MAS/HMS based EAPS² take into account the elements described before but only the static view of them (assuming that no changes will appear during the entire life cycle of the manufacturing system). Few works pay attention to the dynamic nature of these elements. Such works focus solely on the dynamic (run-time) change of the sustainability goals in terms of targets changes but not on new sustainability goals. A literature review on dynamic approaches of EAPS² can be found in [18]. It is derived that an urgent attention to reconfigurable MAS/HMS based EAPS² must be paid by the specialized research community in order to equip this tools with powerful and fault tolerance features demanded by todays and future industrial scenarios.

Finally, it is also important to note that the MAS/HMS based EAPS² is a system itself, for which a LCA can thus be led. This will force designers to adopt a broader view on the different steps of the whole life of their MAS/HMS based EAPS². A LCA for MAS/HMS based EAPS² should arrange the performance-monitoring activities that will trigger/start the reconfiguration of the EAPS² in order to adapt to a change/reconfiguration of the products and manufacturing processes. With such an approach a MAS/HMS based EAPS² may have different versions/configurations depending on the concrete definition of its environment and goals, and may evolve to other versions/configurations when any of these elements changes or when the performance targets are not met. According to this, some holons may appear while other may disappear in the EAPS², the holonic architecture can also evolve to be more efficient. Applying the four main phases for LCA defined by the ISO 14040 [19] and 14044 [20] standards, the steps will be: Goal and scope definition, with a detailed specification of the environment in which the MAS/HMS based EAPS² is currently running, its goals and the performance targets; Life cycle inventory analysis for the input and outputs of the EAPS² taking special attention to the sustainability means; Life cycle impact assessment in order to evaluate the significance of the impacts of the Life cycle inventory results, and; Interpretation to identify, quantify, check and evaluate the need to evolve to other version/configuration depending on the performance targets.

4 Illustrative example

In this part, we provide an illustrative example of the application of previously introduced key-enabling requirements on a MAS/HMS based EAPS², focusing only on the informational and organizational requirements. This example is theoretical and futuristic, but is inspired from a real industrial need and opens some new interesting perspectives for researchers. In this example, a holonic system (consisting of three subsystems) for coordinated scheduling of manufacturing production and energy generation in a region is considered, see Figure 1:

- A Smart Plant #1, which is a factory energy consumer (or a regional supply chain), including a first MAS/HMS based EAPS² for manufacturing scheduling and control, denoted in short "**smart factory scheduler**",
- A Smart Plant #2, which is an energy provider/supplier– including a second MAS /HMS based EAPS² for energy generation scheduling and control, from different regional energy sources, denoted "**smart energy scheduler**",
- A regional MAS for conflict resolution and overall monitoring.

This open and distributed architecture can be seen as a MAS/HMS "system of systems" that provides the possibility to make coordinated decisions on manufacturing activities and energy consumption that should gain from being based on a service-oriented architecture and an enterprise service bus supporting P2P interactions ("peer to peer") [21]. It also comprises a knowledge base system consisting of two major components: an **ontology** that defines a model of domain knowledge and a **world scene** memorizing past events and decisions; mirroring the reality and the evolution in the environment; and reflecting the model of situation with the actual state of all participants in real time. This architecture can be reconfigured (REQ#O2), connections can be made using plug and play technologies to adapt or open this network at any time.

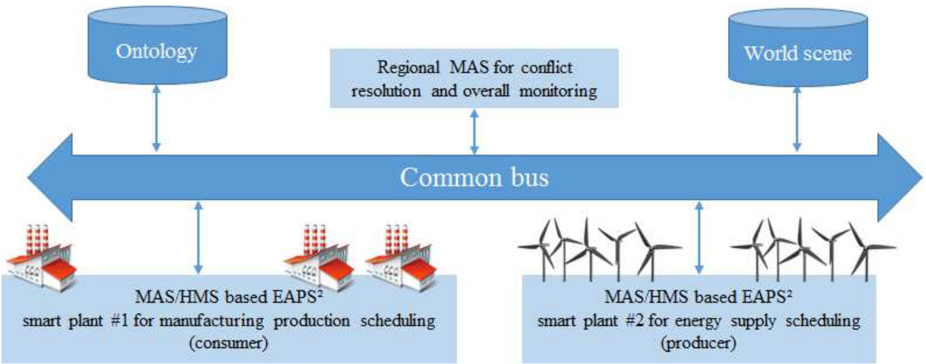

Fig. 1. MAS/HMS "System of Systems" view.

In this example, the top-level regional MAS for conflict resolution and overall monitoring contain agents representing both types of schedulers which receives data about their statuses and plans for the calendar period and time of the day. Smart factory and smart energy schedulers interact with their own ERP and MES systems (REQ#I1) to get production plans, batches of operations and their status. Each of the considered schedulers makes its own resource scheduling: the smart factory scheduler deals with manufacturing orders, processes, equipment and workers in the factory, and the smart energy scheduler deals with energy generation plans, for example, turning "on" or "off" turbines or launching CHP (combined heat and power plant) on coal, taking into account characteristics of orders and processes, supply chains, resource requirements, equipment condition, etc.

The created schedule for each of the systems (producer and consumer) is transferred to the general regional multi-agent system for conflict resolutions, which can ask one or the either systems to reschedule if necessary. If there is no conflict, the role of agents-representatives is the elaboration of fast coordination of plans and the sending of approvals to the schedulers. Meanwhile, in case of important events that violate the balance of interests, special vertical and horizontal protocols for negotiation and conflict resolution can be used.

Let us consider, for illustration purpose, a scenario example:

1. The factory receives at a date t_0 an unexpected new large order.
2. The smart factory scheduler adapts the production schedule, but notes then that it will imply the use of a highly power-consuming equipment.
3. The smart energy scheduler is informed about the forecast in the increase of the energy consumption of the factory. The rise of the power needed is precisely evaluated.
4. Aside this process, the smart energy scheduler is also informed of unexpected variations to come in the availability of the renewable energy part, because of weather conditions. The conjunction of these two processes enables the smart energy scheduler to detect two overload peaks, see fig. 2.
5. The smart factory scheduler receives back precise information about such peak time intervals.
6. The smart factory scheduler tries to short-term reconfigure (REQ#O2) and to rebuild a new production schedule avoiding these peaks, for example, by smoothing production, scheduling factory workers on a night shift, plugging in new production resources (facilitated using the holonic paradigm) or outsourcing part of production (REQ#O2).
7. When finding a solution through iterative negotiation, both schedulers sign an updated agreement, which reflects the new balance of supply and demand.
8. If necessary, and as an illustration of the reconfiguration process (REQ#O2), the top-level regional MAS for conflict resolution can connect in the negotiation process additional smart energy schedulers of other energy providers to improve the level of generated energy on demand, in particular from alternative energy sources (e.g., solar and wind) for time intervals of favorable weather forecast (REQ#O1).

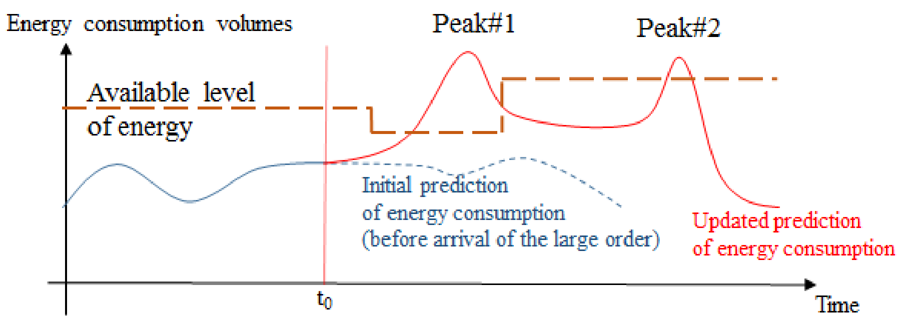

Fig. 2. Graph of energy plan coordination.

Obviously, the energy availability and consumption depend on which other smart factories and smart energy providers are active and connected to this network at that time. There may be not only two as in the given example, but much more. As a result, the situation changes dynamically, depending on many factors. Thus, the global levels of available and required energy are dynamic as well. Similarly, negotiation protocols can be built in case of sudden decrease in energy consumption or introduction of new sources of cheap energy, etc. More, this architecture can not only be expanded by increasing the number of providers and consumers, but also recursively by increasing the number of implemented levels using holonic principles of self-similarities, providing the requirements for openness and flexibility, performance, scalability, reliability and viability.

This example architecture illustrates how the introduced key-enabling requirements force designers of MAS/HMS based EAPS² to have a broader, more global view of the initial energy-aware scheduling design issue as well as help them to open their mind to find new global and original solutions.

Currently the discussed smart factory and smart energy schedulers are under development and are planned to be applied for manufacturing in aviation industry and modelling of regional energy consumption [22], [23].

5 Conclusion

The aim of this paper was to foster researchers to pay attention to key-enabling requirements when designing MAS/HMS based EAPS² beyond requirements directly relevant to the EAPS² system itself. These requirements force widening the attention paid by researchers during design in order to ensure the most global view of the implications of the principles of sustainability at different levels of the manufacturing system and their proper treatment by the concrete MAS/HMS based EAPS². For that purpose, a set of emerging key-enabling requirements was proposed. These requirements were organized according to three different views, namely informational, organizational and lifecycle views. It has been discussed the fact that these key-enabling requirements are not sufficiently addressed by the literature. An illustrative example of a system complying with some of these requirements was provided to illustrate the potential benefits of such a more global design view. From our work, it seems that some of the introduced requirements remain consistent even if they are not addressed within the context of HMS/MAS and we intend to pursue our work in that direction.

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