Sustainable Performance: A Paradigm Inducing New Needs of Interoperability Between Maintenance and Scheduling Activities in Manufacturing

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Abstract

Sustainability, or more precisely the sustainable performance as the social, economic and environmental balance, is a new paradigm for production systems having consequences on their management. In this context, the split of performance in the three dimensions efficiency-effectiveness-relevance, find a new utility to build decision supports for this management. In this paper, we firstly show what are the new stakes related to these three dimensions. We then point the impact of two short-term activities on these dimensions of sustainable performance: scheduling of manufacturing tasks and maintenance of manufacturing systems. We review some scientific works on these subjects, and we show how some of them could contribute to needed efficiency, effectiveness and relevance. This review leads us to discuss the needs of interoperability of maintenance activities and manufacturing scheduling, to underline scientific issues related to this interoperability, and to propose future research directions to improve it.

Keywords: *sustainability, manufacturing scheduling, maintenance, interoperability, ontology.*

1. Introduction

Sustainable performance is a long term performance hinged on three dimensions: social, environmental (or ecological), and economic. Even if the concept appeared more than fifteen years ago under the terms "triple bottom line" (Elkington 1998 and Asselot 2011), its application remains marginal in the corporate operational management. Whereas some efforts can contribute, as collateral consequence, to reducing the environmental and social impacts of industrial activity, most companies continue to have their strategic, tactical or operational targets based on essentially economic criteria (turnover, productivity, return of investment ...). Sustainable performance requires the ability of a company, through its governance practices and market presence, to positively influence ecosystems (improving natural resources, reducing pollution levels, etc.), society (supporting local populations, creating employment etc.) and economic development (distributing wealth through dividends, paying fair salaries, respecting supplier payment obligations etc.) (Sustentare 2010). To correctly perceive the concept of sustainability and to implement it in corporate management in accordance with corporate strategy requires (Krechovská and Procházková 2014): integrate sustainability into the business process management (sustainability must become an integral part of strategic management and business planning), integrate sustainability into the measurement and performance management (quantify the effects of sustainable activities in the financial performance and its impact on the growth of shareholder value), and identify appropriate business performance metrics (identification of social, environmental and economic indicators that influence the success of an organization).

For this, some researchers have worked on the development of sustainable scorecards and associated frameworks (Nikolaou et Tsalis 2013) starting from the approach called "Balanced Scorecard" introduced by (Kaplan and Norton 1996). These works have revealed weaknesses in the way operations are driven in companies, and the lack of objective appreciation of environmental and social indicators, resulting from the perception of managers.

In this paper we are particularly interested by the manufacturing firms, and by the low-level short-term or even real time decisions applied to manufacturing systems (Upper levels, such as mid-term production planning, supply chain and business levels are not considered here, as well as lower levels dealing with actuators/sensors and physical behavior are not considered either). Several reasons justify this choice (Trentesaux and Prabhu, 2014). First of all, energy (its growing volatility and cost, its consumption during manufacturing and its losses, to name a few) are becoming to be among the most important drivers in short-term manufacturing decisions. Second, major risks of unsustainability come from the manufacturing processes themselves (pollutant, chemical risk …). Third, with the succession of economic crises, industrialists face a lowering of their activities, which implies a reduction of the use of their manufacturing systems that have, for most of them, been designed to produce at a maximum rate and not designed to produce less for a long period. Despite this, a recent literature review has shown that studies focusing on sustainability issues at a short-term manufacturing level are clearly lacking (Trentesaux and Prabhu, 2014). More precisely, and among all possible relevant topics, this paper focuses on two of the most important short-term manufacturing level functions that are scheduling and maintenance and studies the way a better interoperability of these two functions can improve the whole sustainability of the manufacturing processes. From a sustainability point of view, considering simultaneously scheduling and maintenance is worth studying because of several aspects. In this paper we consider two among them. First, scheduling manufacturing resources without paying not enough attention to their maintenance may lead to losses of performances not only related to the classical availability and reliability issues, but also to the one related to the uses of means required to make production (eg., extra needs for energy and supply) and the consequence of the production itself (increase of scrap level, injury risk exposure, accelerated aging of resources, …). This point has specific impacts on economic and environmental dimensions of sustainability, but too on the social one (for example on working comfort or even security, impacting social ambience).Second, the objectives of scheduling and maintenance are known to be conflictual in the sense that if you maintain too much, you don't produce and if you produce without considering maintenance, you may face serious production capacity issues. Thus, a balance of scheduling and maintenance activities led in a global sustainable way of thinking and designing would help to globally optimize the short-term manufacturing operations in both dimensions least often considered: environmental and social.

In such a context, one key issue is relevant to the way classical short-term manufacturing performance indicators that are, for most of them in scheduling and maintenance, effectiveness-oriented, must be improved to consider also the use of mean, which refers more globally to efficiency. But this proposed evolution will logically complicate the decisional processes in jointly considered production and maintenance design, which becomes by essence multi-criteria and conflictual. This is why this paper also intends to provide some insights to handle this issue in the near future.

2. Efficiency and Effectiveness in short-term manufacturing decisions

Performance is commonly expressed in terms of relevance, efficiency, effectiveness and effectivity (Sénéchal and Léger 2004). Given our concerns to support decisions taken in short-term manufacturing processes the finality of the manufacturing system is not addressed, nor of its constitutive resources (as a result relevance and effectivity are not considered here). Efficiency is commonly considered as the articulation between the means and the results of a given process, and effectiveness as the articulation between its results and the objectives that have been allocated (Trentesaux and Prabhu, 2014). Roughly speaking, efficiency is so often assimilated as "doing things right" while effectiveness, "doing the right things" (Roghanian et al.,2012). Considering jointly environmental and economic dimensions, a sustainable manufacturing system should realize the expected added and so marketable value (maximum effectiveness) using minimal resources (maximum efficiency), this for maximal benefit and for minimal consumption of input means (such as energy) as well as for minimal emission (of pollutants, GHG, scraps…). The next parts deal with sustainability-oriented scheduling methods first, and second, sustainability-oriented maintenance methods. For each part, a short literature review according to this typology is presented.

3. Sustainable Manufacturing scheduling

Focusing on scheduling methods in the proposed context, two main kinds of approaches can be identified in the literature. The first one considers only the scheduling issues without any attention paid to maintenance. Despite this lack of attention, some insights can be found because some of relevant contributions provide interesting breakthroughs toward sustainable scheduling. The second one deals with scheduling with attention paid to maintenance, whether in a sustainable way or not. For this kind, insights concern the way scheduling and maintenance can be articulated.

3.1 Sustainable scheduling without attention paid to maintenance

Sustainability in scheduling is becoming more and more studied. From our point of view, a manufacturing scheduling method can be considered as sustainability-oriented when this method considers, in addition to usual effectiveness-oriented production objectives and indicators (time-based or time/quantity-based), efficiency-oriented objectives and indicators (Trentesaux and Prabhu, 2014). These efficiency-oriented indicators and objectives concern typically "input" means (that is, means required to realize the scheduling: energy, inventory, money, human resources…) and/or "output" means (that is, estimated/measured consequences of the scheduling when realized aside the principle result itself, that is the products, typically: scrap, pollution, energy loss, generated GHG, human injuries, etc.) when computing/constructing these schedules.

A review (not described in this paper) has been made to point out the strong points and limitations of the existing literature. The conclusions are that three kinds of policies have been addressed in a balanced way. In the first kind of policy, a trade-off (balance) between effectiveness and efficiency indicators is realized. It consists typically in minimizing input means consumption while maintaining the global performance as a compromise, decisions being made using a mono or a multi-criteria aggregation method. In the second kind of policy, effectiveness is optimized under efficiency indicators as hard constraints (eg., expressed in terms of maximum costs or maximum available power for given time windows, typically in the smart grid, or more simply, a maximum peak power value to be respected). In the last type of policy, effectiveness is maintained as the main objective, while efficiency is optimized in a second stage and if possible. Typically, opportunistic energy savings are relevant to this approach.

As an illustration of the first kind of policy, (Zhang et al., 2012) proposed a model aiming at optimizing energy consumption and the schedule effectiveness simultaneously. Production resources are characterized by different energy consumptions for different production speeds, which enable the program to find optimal solutions. As an illustration of the second policy, (Bruzzone et al., 2012) have proposed the integration of an energy-aware scheduling (EAS) module used in a second step, after the use of a classical advanced planning and scheduling (APS) system. As an illustration of the third type of policy, (Mashaei and Lennartson, 2013) proposed a scheduling approach for flow shop aiming at gaining the energy consumption of idle machines, while obtaining the desired throughput for the plant as the major constraint. A mixed integer nonlinear minimization problem was provided. An optimal schedule for the operation of the plant and the minimal energy consumption in the idle machines was then computed. These illustrative works mainly focused on input means as the main driver for efficiency. More, in the literature, one can easily face that among the input means, energy is the most addressed one. Other contributions consider the output means in scheduling and historical contributions belong to this category. For example, (Grau et al., 1995) early addressed the issue of waste management during set-up and clean-up tasks in batch chemical industry by finding optimal scheduling based upon an optimal recursive permutation procedure in tasks scheduling.

Another kind of contributions, more rare, consider simultaneously input and output means as key drivers for efficiency. For example, (Fang et al., 2011) proposed a multi-objective mixed integer programming formulation for flow shop scheduling considering different production speeds. The originality of the proposal is that both energy saving and carbon footprint are considered as well as the classical production makespan in the objective function. Application concerns an industry-inspired two-machines flow shop problems. Conclusions are focused on the complexity of the solving on the simplified proposed case study, implying the need to develop more reactive and effective algorithms.

Last, from our review, it was also noticeable that the social pillar has seldom been addressed by the scheduling community since it is more relevant to humanities and social sciences and not directly concerned by engineering sciences. Meanwhile, we can identify a real overlapping focusing on ergonomics, mental workload and cognition, decision aid and human-machine systems, see as an illustration of this overlapping the work presented in (Trentesaux et al., 1998).

3.2 Scheduling considering maintenance

From our review, it is noticeable that when manufacturing operations scheduling and maintenance are simultaneously considered, it was most of the time with no attention paid to sustainability issue. In fact, some methods for production scheduling considering maintenance have been proposed for a long time. Meanwhile, proposals were made using only effectiveness-oriented indicators and objectives, the operation research community being one of the most active in this field. As typical illustrations of this kind of contribution, let us mention two works. (Gao el al., 2006) proposed a hybrid genetic algorithm to schedule jobs and maintenance activities in flexible job shop aiming to minimize time-related criteria (effectiveness-oriented, no attention paid to efficiency). More recently, (Xu et al., 2015) proposed a single-machine scheduling problem with workload-dependent maintenance duration where the objective is to minimize total completion time, and so efficiency-related criteria are not considered.

3.3 Conclusion of the review for the scheduling function

It was faced that among all the contributions studied from the scheduling research community, few addressed also maintenance and sustainability simultaneously. It was “scheduling plus sustainability” (no attention paid to maintenance) on the one side or “scheduling plus maintenance” (no attention paid to sustainability) on the other side. The reason why sustainability is seldom addressed when designing scheduling systems that consider maintenance (as an objective or a constraint, cf. policies) is mainly due to the complexity generated and the habits from the different research communities. Indeed, even without considering efficiency (and more generally, sustainability), effectiveness-oriented objectives used to design scheduling methods are by essence conflictual with the ones from maintenance. Adding another dimension related to the efficiency will complicate more this situation if classical solving approaches are used. The following part details in a symmetric way, the maintenance as the main function and identifies its relationships with sustainability and scheduling. Provided these two reviews, a new way to consider the relation between maintenance and scheduling from a sustainable point of view will be proposed.

4. Sustainable maintenance for sustainable-efficiency

4.1. Sustainable maintenance without attention paid to manufacturing scheduling

Industrial Ecology, mainly defined as the sustainability science (Ehrenfeld 2004), put the maintenance activity in the perspective of the whole life-cycle of products. In a holistic approach or system thinking approach, it leads to take into account system complexity and multidisciplinary vision to manage asset as a whole (Iung and Levrat 2014). It follows a set of new approaches and concepts consisting naturally to act on the design of the product and / or the manufacturing process, and so rarely in short-term manufacturing decisions. Green maintenance, attempts to make maintenance more environmentally benign by eliminating all waste streams associated with maintenance, and consisting for this in the integration of product design issues with issues of maintenance planning and execution aimed at minimizing negative environmental effect (Ajukumar and Gandhi 2013). Life-cycle maintenance consists, for a given product, in managing maintenance and dismantling activities in an effective way throughout its life cycle. For this, some authors suggest to build maintenance management on three feedback loops in order to adapt maintenance strategies to various changes such as those in the operation conditions and environment (Takata et al. 2004). At last, as a part of the circular economy, maintenance can be seen first as enabling system to sustain the artefact all along its life cycle, then as a key tool to keep the regeneration potential of this artefact and finally as a target system requiring also to be sustainable (Iung and Levrat 2014).

We identified two maintenance strategies covering shortest-term decisions: Total Productive Maintenance (TPM) and Opportunistic Maintenance (OM) (Day and George 1982). TPM optimizes equipment effectiveness, eliminates breakdowns and promotes autonomous maintenance by operators through day-to-day activities involving total workforce. While this strategy is initially interested in improvement of economic impacts (overall equipment effectiveness (OEE)), it acts positively on the most rarely considered social dimension: through the improvement of the safety (improving workplace environment, eliminating hazardous situations), of the moral (increasing of employees' knowledge, involvement and empowerment), and of the social relations (managing synergic cooperation of production and maintenance) (Ahuja 2008). But the cooperation is here more developed in the execution of preventive or corrective maintenance tasks, than in their scheduling. Many authors argue that the maintenance strategy the most adapted to the new challenges of lean manufacturing systems is the OM. OM is defined as a systematic method of collecting, investigating, preplanning, and publishing a set of proposed maintenance tasks and acting on them when there is an unscheduled failure or repair "opportunty" (Savic et al. 1995). The first application of this concept involves the scheduling of maintenance activities themselves. In this context (Xia et al. 2012) propose a multi-attribute model (MAM) to optimize the maintenance schedule cycle by cycle, allowing to establish a tradeoff between equipment availability and maintenance cost. The aim is to conduct preventive maintenance activities to lengthen the available lifetime by reducing the cumulative failure risk, while a minimal repair is used on the system if it fails between successive PM activities. We could consider here to be in search of efficiency of maintenance. But the main expected result being the availability of equipment, there is no control the overall efficiency of the system. To achieve this overall (eco)efficiency, it seems essential to consider jointly maintenance and manufacturing scheduling.

4.2. Maintenance considering manufacturing scheduling

There are few works focusing on maintenance considering manufacturing operations at the same time, and most of the time manufacturing operations are assumed to be constraints to be respected and the global objective can be expressed in terms of effectiveness with no attention paid to efficiency. In such a context, two approaches can be identified. A first approach consists in assuming that production scheduling is given and that maintenance tasks, both preventive and curative, have to be inserted dynamically in these schedules. For this, (Aissani et al. 2008) proposed a multi-agent approach for the dynamic maintenance tasks scheduling for a petroleum industry production system. Agents simultaneously insure effective maintenance scheduling and the continuous improvement of the solution quality by means of reinforcement learning. In these works, the main objective of the petroleum industry was to produce the exact quantities of the flow stream requested by the client, and in the good delivery time. We stay so here in a search of effectiveness. A second approach considers maintenance in an opportunistic way. For example, the "bi-level maintenance strategy" proposed by (Xia et al. 2015), based on a multi-attribute model, leads to a production-driven OM policy for batch production. With sequential preventive maintenance advancement or postponement, the obtained maintenance policy eliminates unnecessary production breaks by utilizing set-up opportunities between successive batches. The adjustment is dynamically chosen at each setup opportunity, and based on cost savings. This strategy focuses on the effectiveness of the system-level scheduling, and mainly is used to obtain maintenance intervals based on availability maximization and maintenance cost minimization. In addition, manufacturing scheduling is not here further questioning.

4.3. Conclusion of the review for the sustainable maintenance

In a symmetric way than above about manufacturing scheduling, our review focus on maintenance activities showed a lack of developments on sustainable maintenance at the short-term level, leading to sustainable efficiency through integrated maintenance-manufacturing scheduling. One reason for this ascertainment is the difference of temporality of the three concepts: sustainability (more often measurable on the life cycle of products/equipment), maintenance (deducted from lifetime of components when preventive, and carried out as soon as possible after detection of a failure when corrective) and manufacturing scheduling (more often built on intermediate temporal horizons and frequencies). A second reason is the divergence of concerns and of language, between production managers and maintenance managers (see conflictual consequences cited in 3.3.), and even more prevalent divergence between engineers, persons in charge of quality, health and safety, accountants, and human resource managers, all being able to appreciate economic, environmental and social performances. Some answers to these problems lie in the multi-criteria approaches mentioned in 2, and multi-agent approaches described in 4.2., and in the two following levers.

The first lever is the last advances on prognostic and health management, as new solutions to allow an expert to make use of future opportunities, in an "opportune" rather than "opportunistic" approach. For example, (Thomas et al. 2009) suggested to define an opportune maintenance through two notions that are proximity and accessibility of components maintained. We suggest extrapolating opportune maintenance to opportune manufacturing, considering jointly prognostics on manufacturing fluctuations and on failures of equipment to adjust joint manufacturing / maintenance scheduling. Adjustments of manufacturing scheduling could be based on proximity of manufacturing machines and on their reconfiguration/setup capacities. The second lever is the interoperability between manufacturing process and maintenance process, which we develop in the next paragraph.

5. Issues and propositions about interoperability

5.1. Questions about Interoperability between maintenance and manufacturing

The most common motivation of works about interoperability between maintenance and manufacturing is the objective to share knowledge and conciliate uncertainties related to the temporal demands of production, machine failures and downtime costs (Rezg et al. 2012; Mosallam et al. 2012). In their systematic review of the literature on manufacturing systems, (Negahban and Smith 2014) show that the planning and scheduling of maintenance operations topic represents only 7% of the studies against 30% of articles dealing the planning and scheduling of manufacturing operations. To illustrate this scenario (Oztemel and Tekez 2009) make the division of production functions in 9 parts and 4 levels, maintenance management being considered as a part of the third level of and it directly related to the level called 'manufacturing function'. The information in the companies, according to (Tursi and al. 2007), are basically arranged on two levels: at the business level through systems type Enterprise Resource Planning (ERP), and at the production level by systems type Manufacturing Execution System (MES). These authors assert that in these levels, barriers in knowledge management and interferences in communication arise and the creation of ontological models allows to improve the semantic interoperability and the creation of standards, essential for interoperable systems. Moreover, (Karray et al. 2009) also point out the issue of inconsistency and redundancy of these support systems, claiming they are based on different models and advocating the need to implement the integration of maintenance support system in a unique global platform for managing maintenance. The authors in (Malucelli et al. 2006) corroborates this view stating that the problems associated to the heterogeneity of data and knowledge systems is a major obstacle to the interoperability of systems. (Jabrouni et al. 2011) say that semantic technologies are essential to ensure that the informations exchanged by heterogeneous and distributed systems are integrated, and thereby solve the problem concerning the conceptual and semantic barrier to interoperability.

On this issue, (Stark et al. 2014) show that in the context of Life Cycle Engineering (LCE), one of the main problems for the integration of sustainability concepts is to formalize and define these concepts on the basis of an integrated data management in order to find a solution that is truly in the sustainable context. In many cases, the data in the sector of Maintenance, Repair and Overhaul (MRO) are not horizontally integrated with customers, suppliers by the ERP, PDM (Product Data Management), DMS (Document Management System) and CMMS (Computerized Maintenance Management). Similarly, the data are not vertically integrated with MES (Manufacturing Execution System), SCADA (Supervisory Control and Data Acquisition) or by PLC (Programmable Logic Controller).

As a response to these issues (Pandey et al. 2011) had set up a joint optimization model of the quality control, production scheduling and maintenance scheduling. First, they make the association between the maintenance intervals and the control charts to minimize the cost per unit of time. After that, the optimized interval of preventive maintenance is associated to the production schedule with the objective to establish the optimal sequence of production. (Marquez and Gupta 2006) discuss the integration between the systems type ERP and CMMS, meant to add and make unification of data with its corresponding codification in order to attempt to semantic requirement.

5.2. Proposition based on ontologies

In this section we present an integrated preliminary approach relating production planning and maintenance, the last being observed in the context of opportunistic maintenance. The integration between production planning and scheduling, as well as the three strategies associated with this integration according to (Maravelias and Sung 2009), is not observed in this article. Finally, the article will not deal with the issue of structural or technical interoperability, but being focused on the organizational interoperability, defined in (Vernadat 2010) as a way to coordinate the different business processes, defining the synchronization steps and coordination mechanisms of collaboration. To develop this propositional framework, the model is considered from the point of view of semantic approach and knowledge structuring, leading also to semantic interoperability concerns. The goal is information processing related to production tasks and maintenance. The Fig. 1 illustrates the main framework components. At the top of this figure a relation between production and maintenance is fulfilled through OEE (Overall Equipment Effectiveness) a well-established industrial indicator. This indicator is associated with Triple Bottom Line (TBL) in order to incorporate economic, environmental and social dimensions to production and maintenance activities, at the level of tasks to be performed by both sides.

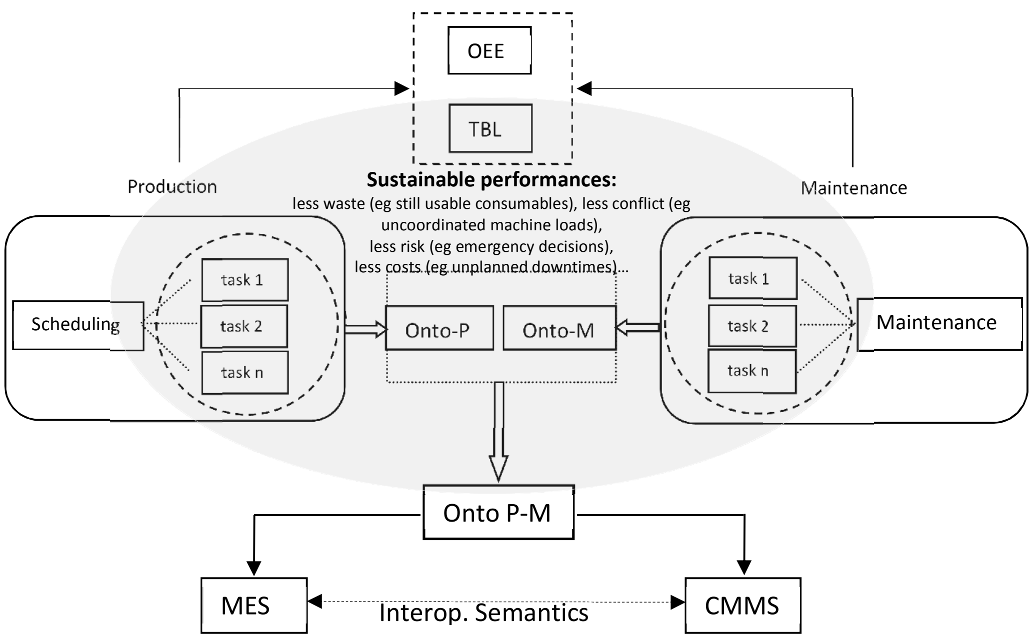

Fig. 1. Sustainable Performance Interoperability Framewok

A management system of production according to (Shobrys and White 2002), defines the long-term actions (programming), short-term actions (scheduling) and real-time actions (process control). To (Muñoz et al. 2011), scheduling basically consists of calendar, resources and associated tasks definition. Decision making of production programming according to (Maravelias and Sung 2009), can be considered to be a set of tasks assignment to processing unities with the respective calendar of each unity, associated with Network-based and Back-based approaches. The integration of this set of information to knowledge transforming, to (Muñozet al. 2012), passes primarily through information standardization, and may be based on ANSI/ISA 95 or IEC 62264 standards for a better efficiency on the flow of information. In this context, ontology can be used as means of sharing this information to solve integration, structuring and synchronization issue of heterogeneous systems. Fig. 1 represents this ontology as Onto-P.

To increase the efficiency of production scheduling, answering effectively to its programming, the action of maintenance should be jointly observed, adopting as a strategic model the opportunistic maintenance. Karray, Morello and Zerhouni (2009) comment on the need of maintenance organization to consistency of actions of the production system. To the same authors, integrated services are vital to complex tasks, with the information exchanged between systems as an obstacle to the interoperability of these services. To finish, the authors state that the architectural structures of systems must pass from the static form to a more intelligent form based on semantic interoperability, and for this, on the s-maintenance concept, they highlight the use of ontologies representing three levels: the general maintenance concepts, the application domain and the specific needs of each company. (Karray et al. 2011) point out the need to share an ontology in common with maintenance, with their associated rules, to have an interoperable communication. Fig. 1 represents this ontology as Onto-M.

The integration of these systems, according to (Harjunkoski et al. 2009), must appear from the functionality of the same systems and the need to fulfill workflow tasks. The authors still comment that the decision making tools operate in an isolated way ignoring local needs, thus disfavoring global decisions. This integration can be seen in Fig. 1, represented by an ontology called Onto P-M. The construction of this ontology can be observed by the interoperability approach, based on models of driven architecture (Model-Driven Architecture - MDA). To (Baina, Panetto and Benali 2006), such an approach facilitates the exchange of information between different applications, and is based on the definition of four ontological levels. Still according to the authors, MDA approach formalizes the interoperability semantic problem between different applications. Finally, (Vernadat 2010) comments that ontologies based on semantic interoperability is a strong research field, being the semantic unification of concepts one of the main challenges. The author also cites four different approaches about this question: ontologies mapping, ontologies alignment, ontologies transforming and the fusion of ontologies. These stand for the branches of the research development characterized by the proposed framework.

6. Conclusion

In this paper, we showed that manufacturing scheduling and maintenance have an important impact on sustainable performance. We explored a set of scientific approaches used to improve decisions on production manufacturing, or on maintenance activities, and aiming to obtain effectiveness more often than efficiency, and never on the three joint dimensions (economic, social and environmental). Among several causes of this observation, we suggest to improve interoperability between maintenance and production. Referring to recent works on this subject, we propose a framework considering the organizational interoperability as a way to coordinate the different business processes, and defining the synchronization steps and coordination mechanisms of collaboration required.

Further works will consist in the implementation of this interoperability through new ontologies or meta-ontologies for joint sustainable performance in production and maintenance.

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