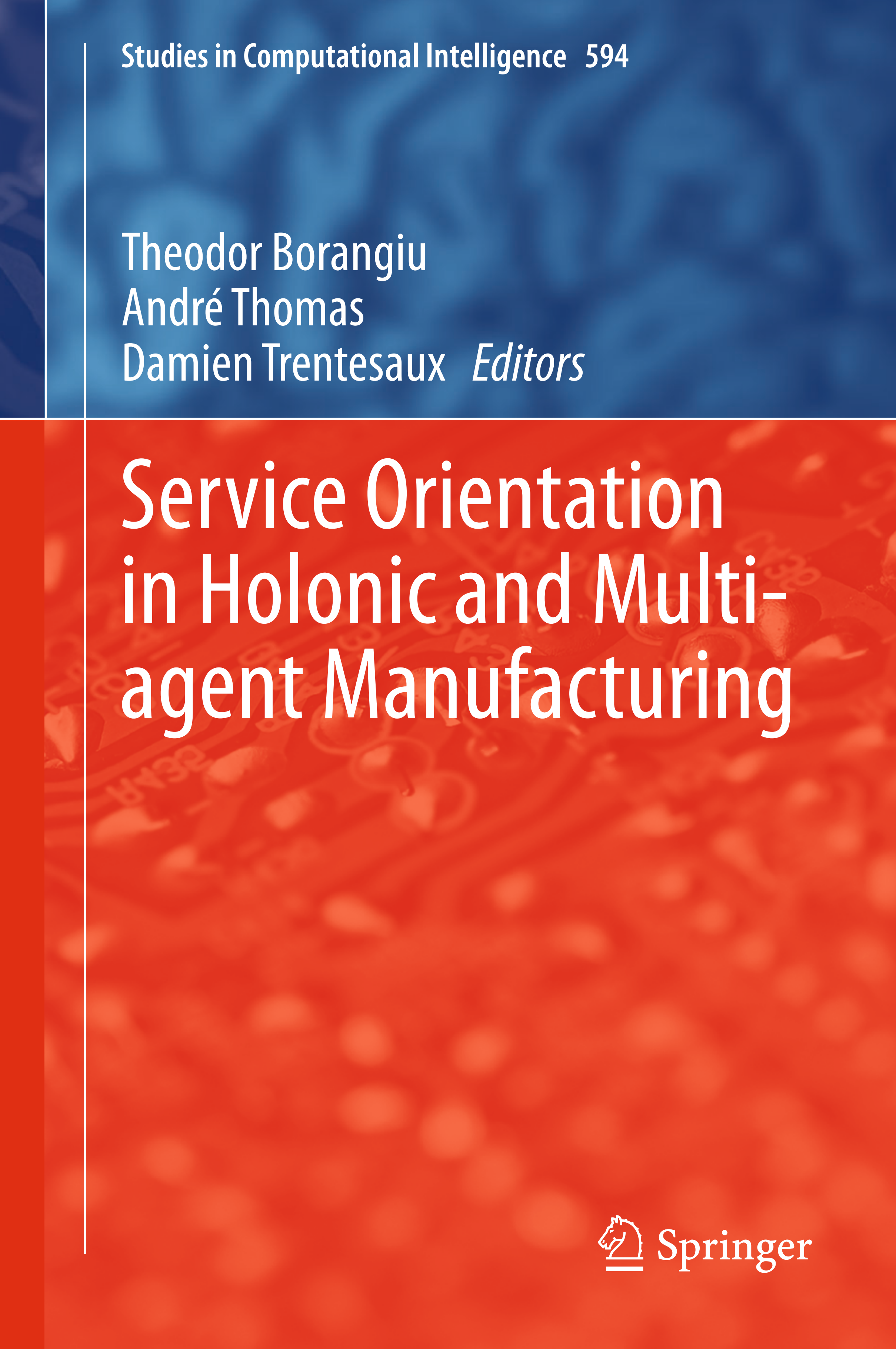

Studies in Computational Intelligence 594

Theodor Borangiu
André Thomas
Damien Trentesaux *Editors*

Service Orientation in Holonic and Multi-agent Manufacturing

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Theodor Borangiu · André Thomas
Damien Trentesaux
Editors

Service Orientation in Holonic and Multi-agent Manufacturing

Springer

Editors
Theodor Borangiu
Department of Automatic Control
and Applied Informatics
University Politehnica of Bucharest
Bucharest
Romania

Damien Trentesaux
LAMIH UMR CNRS 8201
University of Valenciennes
and Hainaut-Cambrésis (UVHC)
Valenciennes
France

André Thomas
Research Centre for Automatic Control
Nancy University
Epinal
France

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Foreword

Twenty three years ago when I was working at BHP Co. Ltd. running an automation and control research programme in the steel industry, I was presented with the opportunity to become involved in the newly formed Holonic Manufacturing Systems consortium. It was one of the six consortia being formed under the umbrella of the global Intelligent Manufacturing Systems (IMS) programme. After an initial glance, I prepared to discard the request. The steel industry at that time (and ever since) was in cost-cutting mode, our research was very short term in focus. I needed sponsorship for such an endeavour from our steelwork operations and I simply could not envisage convincing any of my industrial control colleagues to become involved. However, I dutifully bundled off some documentation and sent it to our Newcastle and Port Kembla steelworks noting that such developments might help BHP Steel manage some of the rapid market changes that it often faced. The response was surprising. I received an emphatic “Yes” from both steelworks who cited examples of production delays, lack of flexibility, lost market opportunities, etc., which they believed could be attributed to excessive rigidity of the production control systems we used. This was deep in the age of Computer Integrated Manufacturing (CIM) where computer control architectures were prescriptive, hierarchically structured and where command-control to ensure smooth operations overrode the need to flexibly adapt. I was particularly told of a lost opportunity within the steel plate operations to meet a market need for a thinner plate than we usually produced. Mechanically, it had been a relatively easy opportunity to adapt the plate rolling mill to execute the additional rolling passes to achieve the new thickness and to determine the changed spray cooling conditions to achieve the correct metallurgy. But it took almost 6 months to be confident that the mills planning, scheduling and control systems could be successfully adjusted. By this time the market opportunity had disappeared.

So into Holonic Manufacturing we went. It literally changed my working life. It took a long time to take root that the main challenges for industrial control were not generally to do with machine control—my previous area—nor generally with offline planning and scheduling but rather in the mushy zone in between where the execution of orders takes place, where material flow has to be controlled and at the same time operations on that material accurately managed. It was also the era when Statistical Process Control (SPC) gained a strong foothold—but only for the monitoring and control of steady operations in steady-state—and in the steel industry as we sought to adjust to changing customer needs—there were more start-ups, change overs and shut downs than ever before.

And when I moved to Cambridge in 1995 I could see that these challenges were widespread across many manufacturing sectors. So the notions of managing manufacturing execution operations under disruptive or changing conditions became a focus and holonic manufacturing and the multi-agent-based control stood out as providing a guiding light as a way of enabling machines to “think for themselves” under changing conditions. Sometime in the mid-1990s people began to wonder whether the product being made might also benefit from thinking for themselves and the seeds of product intelligence emerged. Elsewhere, over the next years, other bio-inspired paradigms were also proposed, and developments in Internet, multi-agent software, flexible logic controllers, radio frequency tagging and real-time data management helped to provide a more convenient platform for developing these solutions.

So in 2014 it was interesting to reflect on the expansion and diversion of this domain. This volume based on the SOHOMA 2014 Workshop provides an excellent snapshot on the current state of work in this area—albeit from a predominantly European perspective. As the editors indicate in their Preface, this book is able to update the reader on a range of developments ranging from distributed AI, the influence of complexity and big data on this domain and extends from manufacturing to consider closely related logistics issues. It will be a very useful addition to your bookshelf!

December 2014 Duncan McFarlane

Preface

This volume gathers the peer-reviewed papers which were presented at the fourth edition of the International Workshop "Service Orientation in Holonic and Multi-agent Manufacturing—SOHOMA'14" organized on November 5–6, 2014 by the University of Lorraine, France in collaboration with the CIMR Research Centre in Computer Integrated Manufacturing and Robotics of the University Politehnica of Bucharest and the TEMPO Laboratory of the University of Valenciennes and Hainaut-Cambrésis.

SOHOMA scientific events have been organised since 2011 in the framework of the European project no. 264207 ERRIC, managed by the faculty of Automatic Control and Computer Science within the University Politehnica of Bucharest.

The book is structured in six parts, each one grouping a number of chapters covering a specific research line which represents a trend in future manufacturing control: Part I: *Holonic and Agent-based Industrial Automation Systems*, Part II: *Service-oriented Management and Control of Manufacturing Systems*, Part III: *Distributed Modelling for Safety and Security in Industrial Systems*, Part IV: *Complexity, Big Data and Virtualization in Computing-oriented Manufacturing*, Part V: *Adaptive, Bio-inspired and Self-organizing Multi-Agent Systems for Manufacturing* and Part VI: *Physical Internet Simulation, Modelling and Control*.

These six evolution lines have in common concepts related to *service orientation* and *enterprise integration*, with *distributed intelligence* for activities planning and control in *holonic* and *agent-based* industrial environment; today it is generally recognized that the Service-Oriented Enterprise Architecture paradigm has been looked upon as a suitable and effective approach for industrial automation and manufacturing management and control.

Manufacturing systems are amongst the most complex and demanding artefacts in modern society but also amongst the most valuable ones. The challenges include coping with their heterogeneous nature and their online interactive nature in combination with competitive pressures. Offline plans are known to become invalid soon after arriving in the shop floor. Therefore, researchers are looking into matching technologies which are able to answer these challenges. *Holonic systems* are, actually by definition, targeting such challenges. *Agent technologies* focus on interactive and decentralized aspects. In particular, developments aim to deliver open systems and system components, as well as infrastructure and infrastructural components rather than closed systems.

Technological advances in wireless sensor networks are enabling new levels of distributed intelligence in several forms such as active products that interact with the working environment and smart metering for monitoring the history of products over their entire life cycle and the status and performances of resources. These distributed intelligences offer new opportunities for reducing myopic decision-making in manufacturing control systems, thereby potentially enhancing their sustainability. Control architectures switch their modes of operation to adapt to severe disruptions. *Manufacturing sustainability* is addressed in this special issue with respect to: fault-tolerance to resource and communication breakdown; energy efficiency at resource and shop floor level; balancing resource usage; cost efficiency and inline quality control of products. Innovative services will be growth enablers and drivers of next generation manufacturing enterprises that are competitive and sustainable.

Several frameworks are proposed for classifying, analysing initiatives and potentially developing distributed intelligent automation systems. These frameworks will be referred to in the book as *Distributed Intelligent Automation Systems*. In particular, there is interest in systems in which the planning or execution of tasks normally associated with a centralized operational level are reassigned to be carried out instead by a number of units cooperating at various levels. Or conversely, a task traditionally using information from a single source should be able, in a distributed information system, to make use of data spread across a range of operations—and potentially a range of organizations (the case of networked, virtual enterprises).

The book defines and explains ways to implement intelligent products by putting intelligence at the object (Intelligent Embedded Systems) or through the computing network (using Automatic Identification and Data Capture technology at the product to allow it to be identified and tracked, and take decisions in a computing architecture). These technologies enable the automated identification of objects, the collection of data about them and the storage of that data directly into computer systems.

The service-oriented multi-agent systems (SoMAS) approach discussed in the book is characterized by the use of a set of distributed autonomous and cooperative agents (embedded in smart control components) that use the SOA principles, i.e. oriented by the offer and request of services, in order to fulfil industrial and production system goals. This approach is different from the traditional Multi-agent Systems (MAS) mainly because agents are service-oriented, i.e. individual goals of agents may be complemented by services provided by other agents, and the internal functionalities of agents can be offered as services to other agents (these service-oriented agents not only share services as their major form of communication, but also complement their own goals with different types of external provided services).

Special attention is paid in the book to the framework for manufacturing integration, which matches plant floor solutions with business systems and suppliers.

This solution focuses on achieving flexibility by enabling a low coupling design of the entire enterprise system through leveraging of Service-Oriented Architecture (SOA), Cloud computing and Manufacturing Service Bus (MSB) as best practices.

The *Manufacturing Service Bus* (MSB) integration model described in some papers is an adaptation of ESB for manufacturing enterprises and introduces the concept of bus communication for the manufacturing systems. The MSB acts as an intermediary for the data flows, assuring loose coupling between modules at shop floor level.

The book offers a new integrated vision combining complementary emergent technologies which allow reaching control structures with distributed intelligence supporting enterprise integration (vertically and horizontally) and running in truly distributed and ubiquitous environments. Additionally, the enrichment of distributed systems with biology-inspired mechanisms supports dynamic structure reconfiguration, thus handling more effectively condition changes and unexpected disturbances, and minimizing their effects. As an example, the integration of service-oriented principles with multi-agent frameworks allows combining the best of the two worlds, and to overcome some limitations associated to MAS, such as interoperability.

A brief description of the book chapters follows.

Part I reports recent advances and ongoing research in *Holonic and Agent-based Industrial Automation Systems*. Nowadays, industries are seeking for models and methods that are not only able to provide efficient overall production performance, but also reactive, facing a growing set of unpredicted events. One important research activity in the field focuses on holonic/multi-agent control systems that integrate predictive/proactive and reactive mechanisms into agents/holons. The demand for large-scale systems running in complex and even chaotic environments requires the consideration of new paradigms and technologies that provide flexibility, robustness, agility and responsiveness. Holonic systems are, actually by definition, targeting challenges that include coping with the heterogeneous nature of industrial systems and their online interactive nature in combination with competitive pressures. Multi-agent systems is a suitable approach to address these challenges by offering an alternative way to design control systems, based on the decentralization of control functions over distributed autonomous and cooperative entities. Some chapters discuss the concept of *Intelligent Product* and related techniques for *Product-driven Automation*.

Part II groups papers analysing *Service-oriented Management and Control of Manufacturing Systems*. Service orientation is emerging at multiple organizational levels in enterprise business, and leverages technology in response to the growing need for greater business integration, flexibility and agility of manufacturing enterprises. Closely related to the IT infrastructure of Web services, the service-oriented enterprise architecture represents a technical architecture, a business modelling concept, an integration source and a new way of viewing units of control within the enterprise. Business and process information systems' integration and interoperability are feasible by considering the customized product as "active controller" of the enterprise resources—thus providing consistency between material and informational flows. The areas of service-oriented computing and multi-agent systems are getting closer, trying to deal with the same kind of environments formed by loosely coupled, flexible, persistent and distributed tasks. An example is the new approach of Service-Oriented Multi-agent Systems (SoMAS). The unifying approach of the contributions for this second part relies on the methodology and practice of disaggregating siloed, tightly coupled business and MES processes into loosely coupled services and mapping them to IT services, sequencing, synchronizing and orchestrating their execution.

Part III treats *Distributed Modelling for Safety and Security in Industrial Systems*. Risk and Hazard Control (RH Control) models are proposed as a basis for developing adequate strategies to avoid the effect of extreme, unexpected events in production systems. Chapters in this section present the state of the art and solutions in risk assessment and industrial safety, dynamic reconfigurability and prevention in manufacturing.

Part IV is devoted to *Complexity, Big Data and Virtualization in Computing-oriented Manufacturing*, which represents major trends in modern manufacturing. Virtualization of manufacturing execution system workloads offers a set of design and operational advantages to enterprises, the most visible being improved resource utilization and flexibility. At the manufacturing execution system level, cloud computing adoption refers mainly to virtualization of MES workloads. While MES implementations are different and usually depend directly on the actual physical shop floor layout, general MES functions are aligned with the functions set defined by ISA-95.03 specification. To achieve high levels of productivity growth and agility to market changes, manufacturers will need to leverage Big Data sets to drive efficiency across the networked enterprise. There is need for a framework allowing the development of manufacturing cyber physical systems that include capabilities for complex event processing and Big Data analytics, which are expected to move the manufacturing domain closer towards digital- and cloud manufacturing within contextual enterprises.

Part V discusses *Adaptive, Bio-inspired and Self-organizing Multi-Agent Systems for Manufacturing*. The dynamic change of the client's needs, leading to higher exigency, may require a smart and flexible automatic composition of more elementary services. Several bio-inspired approaches have been proposed; some are based on stigmergy like the ant colony optimization or the Fiery Algorithm; others are based on Particle Swarm Optimization: Bee-based Algorithm, Bat Algorithm, Shuffled Frog Algorithm and Roach Infestation Optimization. Such approaches provide intelligent decision-making capabilities of agents to dynamically and autonomously change services selection on the fly, towards more trustworthy services with better quality when unexpected events occur. Competitive self-interested agents providing services best suited for clients through dynamic service composition are also described.

Part VI is devoted to *Physical Internet Simulation, Modelling and Control*. The availability of individual information in open loop supply chains enables new organizations like Physical Internet (PI). The aim of the innovative PI concept is to solve the unsustainability existing in current supply chains and logistics systems.

The papers discuss adaptive storing, warehouse management systems, product intelligence, open tracing container or rail-road allocation problems.

If SOA is the conceptual framework for service orientation of enterprise processes, **Service-Oriented Computing** represents the paradigm and implementing framework for embedded monitoring and control systems with distributed intelligence in *Service-Oriented Enterprise Architectures* (SOEA).

All these aspects are treated in the present book, which we hope you will find useful reading.

Nancy, November 2014

Theodor Borangiu
André Thomas
Damien Trentesaux

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Part I
Holonic and Agent-based Industrial Automation Systems

Engineering of Coupled Simulation Models for Mechatronic Systems

Petr Novák, Petr Kadera, Václav Jirkovský, Pavel Vrba and Stefan Biffl

Abstract Simulation models play a crucial role in testing and fine-tuning of control systems for complex industrial systems. They are important parts of the sustainable, service-oriented manufacturing value chain by facilitating early and efficient defect detection and risk mitigation. However, the design phase of simulation models is time-consuming and error-prone, thus it should be improved to become more efficient. The design of simulation models for mechatronic systems has to cope with two basic challenges: (1) the heterogeneous nature of mechatronic systems, which are described with various overlapping engineering plans, and (2) the separation of monolithic simulations into distributed simulation modules, to better conquer the computational complexity of simulation models. This paper addresses both challenges: (a) we propose an application of semantic integration and linked data for sharing and capturing knowledge for simulation model design between various engineering plans; (b) we explain how to structurally connect simulation modules, which are dynamically coupled. The proposed method utilizes the extended bond-graph theory.

P. Novák (✉) · S. Biffl
Christian Doppler Laboratory for Software Engineering Integration for Flexible Automation Systems, Vienna University of Technology, 1040 Vienna, Austria
e-mail: petr.novak@tuwien.ac.at

S. Biffl
e-mail: stefan.biffl@tuwien.ac.at

P. Novák · P. Kadera · V. Jirkovský · P. Vrba
Czech Technical University in Prague, 121 35 Prague, Czech Republic

P. Kadera
e-mail: petr.kadera@fel.cvut.cz

V. Jirkovský
e-mail: vjirkovsky@ra.rockwell.com

P. Vrba
e-mail: pavel.vrba@fel.cvut.cz

V. Jirkovský
Rockwell Automation Research and Development Center, Prague, Czech Republic

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The simulation modules work independently of each other but with interaction, similar to a multi-agent system. Since the computational execution of coupled simulations is a crucial obstacle especially for mechatronic systems, we show how performance analysis can significantly improve the definition of simulation workflows.

Keywords Dynamic simulation · Semantic integration · Performance analysis · Bond graphs · Industrial processes

1 Introduction

A computer simulation aims at approximating the behaviour of real systems. The simulation is useful for key tasks in the manufacturing value chain, such as model-based control, estimation of unmeasured states, operator training, or decision-making support. Although simulation models can be used to improve a sustainable operation of real plants, to reduce waste, and to save energy, their design phase is time-consuming and error-prone, hence their use is still limited [8]. The engineering process of simulation models should be improved in order to bring simulation benefits into daily industrial practice. This paper addresses the design phase of dynamic simulation models for industrial processes as well as the simulation model performance analysis.

Since industrial processes are becoming large-scale and complex, it is not efficient to develop monolithic simulation models for these systems any more. A current trend is the distribution of simulation models into a set of inter-linked simulation modules. Such a complex simulation workflow is frequently called coupled simulation and can even include real hardware in the simulation loop. The separation of simulations into modules can be compared to an agent-based approach. Simulation modules correspond to agents and one of the research goals is to support the encapsulation of modules according to the holonic approach known from manufacturing control. As well, it is crucial to analyse performance and bottlenecks in the simulation workflows. The presented research is related to the development of the Simulation Integration Framework, see Novák and Šindelář [6] or Novák et al. [7] for further details.

To improve the design phase of coupled simulation models for mechatronic systems, the following research issues were identified:

RI-1**: Semantic integration of engineering knowledge**. Semantic integration Noy and Doan [9] should address the following features and requirements: (1) Industrial systems are large-scale and complex and they are described by various kinds of engineering plans. (2) Most of these systems are of a mechatronic nature. They are engineered based on a collaborative multi-disciplinary process combining diverse, partly overlapping plans. Engineering concepts are locally described in heterogeneous engineering plans and these local representations should be integrated in order to allow describing simulations and their workflows. (3) Engineering process support would save costs and effort for (re-)design and re-use.

RI-2**: Module-based simulation**. To improve the design and execution phases of simulations models, they should be internally created as coupled simulations consisting of simulation modules. Benefits of this simulation architecture can be summarized as follows: (1) Parallelization of simulation execution; (2) Easier maintenance and (re-)design of simulations; (3) Significantly faster initialization of simulation environments; and (4) Simplified testing of simulation modules and their fine-tuning.

RI-3**: Performance analysis of coupled simulation**. An important limitation for simulation use is the computational performance. Coupled simulations should be equipped with performance analysis reflecting: (1) Limited insight of simulation experts into coupled simulation assemblies; (2) Required analysis methods and tools to estimate the performance requirements; and (3) Results of performance analysis should be provided to experts in such a form that identifies bottleneck modules. Based on such results, simulation experts can redefine the simulation modules in order to improve the performance of the whole simulation workflow.

The remainder of this paper is structured as follows. Section 2 proposes the utilization of semantic integration for heterogeneous engineering knowledge integration. Section 3 explains how bond graphs improve the design of coupled simulations and a structure of integration glue modules. Section 4 explains the role of simulation performance analysis for simulations. Section 5 concludes and proposes future work.

2 Semantic Integration of Heterogeneous Engineering Data

This section addresses the *RI-1*, which is focused on the semantic integration of engineering knowledge for the model-driven design of simulation models and the configuration of their runtime workflows.

Semantic integration is a key interoperability enabler for the Semantic Web (Ontology matching) as well as a needed functionality in many classical data integration tasks dealing with the semantic heterogeneity problem. It takes schema descriptions and data (e.g., ontologies in the case of Semantic Web) and determines as its output a semantic alignment—a set of correspondences among the semantically related entities. The correspondences can be utilized for data translation, query answering, or navigation on the web of data.

Semantic heterogeneity means variance in the contents of information and intended meaning that may cause application unusability. Dealing with semantic heterogeneity is thus crucial in every extensive complex system. Three main causes of semantic heterogeneity can be distinguished in these systems [3]:

- *Confounding conflicts* occur when information items seem to have the same meaning, but differ in reality, e.g., owing to different temporal contexts.
- *Scaling conflicts* occur when different reference systems are used to measure a value. Examples are different currencies or length measures, e.g., feet/meters.

- *Naming conflicts* occur when naming schemes of information differ significantly. A frequent phenomenon is the presence of homonyms and synonyms.

To describe the similarity of entities, the following basic similarity measures can be used. The most common techniques are **string-based**, which are methods comparing strings—entity labels (e.g., *n*-gram similarity measure). On the other hand, **language-based** techniques are based on Natural Language Processing methods for extracting meaningful terms (e.g., cosynonymy similarity for WordNet). The next data characteristic to match can be the structure of entities found in the data source schema—**structure-based** similarity measures (e.g., structural dissimilarity on a hierarchy).

Unfortunately, these basic techniques are suitable only for a specific type of dissimilarity. Therefore, they can be considered as the cornerstones of similarity aggregation systems. The problem is how to combine these basic techniques.

Independent similarity measures can be aggregated by means of **multidimensional distances**. Well known multidimensional distance is Minkowski distance:

$$sim\left(x, x'\right) = \sqrt[p]{\sum_{i=1}^{n} sim_i(x, x')^p},$$

where $sim_i(x, x')$ is the ith similarity measure of objects x, x'. The distance is equal to the Euclidean distance for $p = 2$ and to the Chebyshev distance for $p = +\infty$.

More sophisticated aggregation systems are based on **machine learning** techniques. These systems are able to extract unknown correspondences among entities and obtain considerably improved performance when compared to that of existing systems [4].

Similarity measure aggregation suitable for engineering data has to assure the best precision and recall what can be achieved. The typical characteristic of fully automatic aggregation systems is their capability of handling big data structures quickly, but on the other hand, they cannot achieve sufficient precision that the simulation design application needs. The compromise between the speed and quality of a matching output are semi-automatic systems. The MAPSOM framework described in Jirkovsky et al. [5] seems to be a promising solution for engineering applications. The MAPSOM framework is based on similarity measure aggregation with the help of a self-organizing map and user involvement for tuning up the results by means of active learning.

An exemplary engineering plan to be semantically integrated with other plans and software tools is a piping and instrumentation diagram (P&ID), which is depicted in Fig. 1 for the case of a simple tank system. This system should be simulated and its behaviour should be split into three modules, as depicted by module cuts in Fig. 1. This use-case will be used later on in the paper to demonstrate the proposed solution.

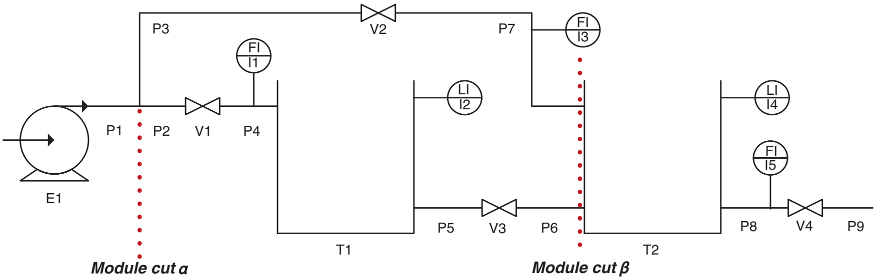

Fig. 1 P&ID of the tank system use-case with selected cuts of the plant into modules

3 Integrating Simulation Modules with Extended Bond Graphs

This section addresses the research issue *RI-2*, which is focused on problems with the design of simulation modules and their integration into simulation workflows. The entry point for this task is a description of a real system obtained by the semantic integration of engineering plans.

A dynamic mathematical model for a physical system can be systematically created based on the bond-graph theory [2]. Bond graphs are based on three types of analogies: (i) signal analogy, (ii) component analogy, and (iii) connection analogy. Bond graphs are based on describing power flows between system components. Power is the product of flow and effort signals that are generic signals defined by the signal analogy. An abstraction of component connection is introduced by the connection analogy. Bond graphs provide 0-junctions as models for parallel connections of components and 1-junctions as models for serial connections of components. Both types of junctions are tackled in a very similar way. An important feature of bond graphs is causality, which is the main difference between bond graphs and power graphs. Causality assignment denotes which of the signals flow and effort is the output variable and which one is the input variable. Causality is denoted in the graphical expression with a small stroke on such side of each bond, where a connected component transfers effort to flow. Further details about bond graph theory and practice can be found in Gawthrop and Bevan [2].

The authors proposed an extended bond graph theory in Novák and Šindelář [6] as a design method to support creating simulations from gray-box components. On top of this method, we explain how to design modularized simulations now.

In order to increase the modularity and computational performance of simulations, the simulation models are frequently required to be split into several simulation modules. These modules are relatively independent, but can be dynamically coupled. We assume that splitting simulations into several modules is driven by a human simulation expert, while the proposed method supports the expert with semi-automating structural and technical tasks. The method supports two basic types of cuts of a plant into modules: (1) cuts on the junction level, and (2) cuts on the bond level.

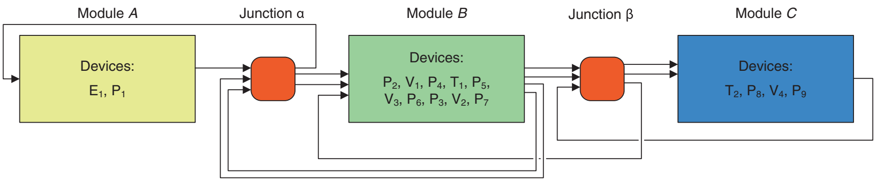

Fig. 2 Coupled simulation for the tank system which consists of simulation modules, integration junctions as "glue modules", and signal routing

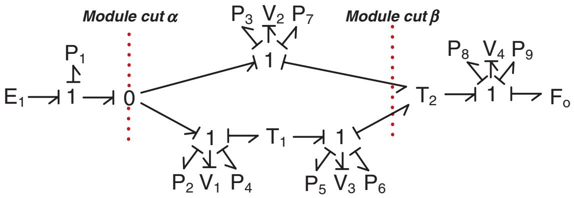

Fig. 3 Bond graph with cuts of the tank system into simulation modules

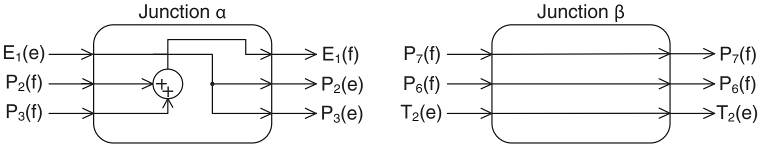

Fig. 4 Internal structure of integration junctions, which is inferred from a system bond graph

A practical example of splitting a simulation of the tank system is depicted in Fig. 2. The system is simulated with three modules, which are connected with two junctions. The junctions can be considered as glue modules, integrating simulation modules. One of the core contributions of this paper is shifting the bond-graph approach to an upper level (i.e., from a device level to a module level) as well as the way how to implement internal structure of these "glue modules" for integration.

Bond graphs can be utilized for designing glue modules as follows. The position of plant cuts is inserted in the bond graph as it is shown in Fig. 3 for the case of two cuts of the tank system. Having such bond graph is important for the design of glue modules. A more complex situation emerges in case of cuts on the junction level, where signals should be added or subtracted. The mathematical expression is obtained based on surrounding bonds and their causality assignments. For the tank system, the glue modules are depicted in Fig. 4. In the case of cut α, the power flows into the 0-junction via a bond from the left 1-junction. Effort is an input of the 0-junction and the junction calculates output flows as the sum of the two flows to the rest of the system on the right. We can see that the inner implementation of the glue module depends on neighbouring bonds only. However, it is necessary to create the bond graph for the whole system in order to be able to assign causality and power flows correctly. If the cut is on the bond level, the situation is easier and only the pair of signals is assigned as input or output of the glue module. This situation is depicted on the right-hand side of Fig. 4 as the cut β and we can see that the solution is trivial in this case.

In both cases of cut types, the glue modules are important for (i) timing aspects, where the module can provide aggregation of data, re-sampling and synchronization. In addition, (ii) the glue module is useful for the performance analysis as a probe into the system. The proposed method solves the simulation module integration problem from the structural point of view. In addition, it is required to analyse the performance of modules and find bottlenecks in the simulation model schema in order to provide engineers with support for the simulation system optimization and redesign. Such issues are discussed in the following section.

4 Performance Analysis for Coupled Simulations

Performance modelling involves multiple approaches. We have considered some of them for modelling interactions between coupled simulations with focus on the identification of the system bottlenecks and the maximal system performance. Particularly, we have considered the usage of the following performance modelling notations, including their pros and cons:

- Bounded Analysis Based on Operational Laws [1]
  - Pros: Easy to use, no special skills required, low computational demands;
  - Cons: Low expressivity (neither component interactions nor synchronization);
- Queuing Networks
  - Pros: Simple notation, separated characteristics of specific components;
  - Cons: No support for modelling synchronization and joint probabilities;
- Queuing Petri Nets
  - Pros: Transparent graphical modeling notation;
  - Cons: Non-trivial applications generate more states than is feasible to handle;
- Stochastic Process Algebras
  - Pros: High expressivity (synchronization, exclusive access, connections);
  - Cons: Requires special skills, aggregation of states cannot be easily automated.

Based on the pros and cons of these different notations, we focused our attention on the Bounded Analysis (BA), which is based on operational laws [1] and provides a reasonable compromise between the expressivity, usability and runtime solvability. This approach identifies the system bottlenecks and the maximal system throughput. The operational laws are directly applicable in single class cases, but the multi-class cases are more complicated. Therefore, we use a method based

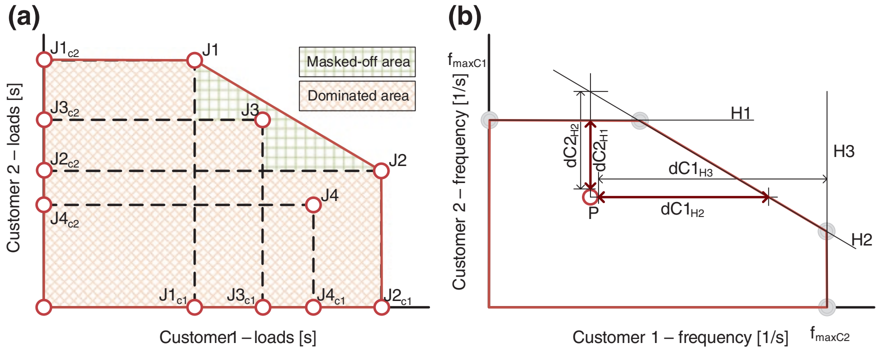

Fig. 5 **a** Loads of individual stations by customer classes and their convex hull, **b** transformation from loads to the frequency space and identification of the reserves

on convex polytopes to identify service stations that may be bottlenecks under certain circumstances. The modelled system must be described by a *Loading matrix* $L[n \times m]$ (n is the number of job centers, m is the number of customer classes), where l_{ij} represents the load (time in seconds) that puts the customer j on the job center i. The loading matrix can be transformed to a m dimensional space, where each axis represents one customer class, and job centres ($J1$–$J4$) are points in this space that indicate, how each customer class loads the particular job centre. The potential system bottlenecks ($J1$ and $J2$) lie on the convex hull of this point (and their projections on all axes) (see Fig. 5a). This plot can be transformed to frequency space of customer arrivals (see Fig. 5b). The current state of the system is represented as a single point P and the distance to the hyperplanes ($H1$, $H2$, $H3$) indicates the maximal frequency increase before a job centre gets saturated. In other words, the system that is in state P can increase the arrival frequency of *Customer 1* by $\mathrm{dC1}_{\mathrm{H2}}$ ($\min(\mathrm{dC1}_{\mathrm{H2}}, \mathrm{dC1}_{\mathrm{H3}})$) or the arrival frequency of *Customer 2* by $\mathrm{dC2}_{\mathrm{H1}}$ ($\min(\mathrm{dC2}_{\mathrm{H1}}, \mathrm{dC2}_{\mathrm{H2}})$).

5 Conclusions and Future Work

This paper summarizes the three important and inter-related problems in the area of simulation model design for industrial mechatronic systems. The paper addresses the research issue dealing with integrating heterogeneous engineering knowledge for simulation model design. It also addresses cutting simulation models into a set of simulation modules. The paper proposes a methodology for designing glue modules integrating the simulation modules. Finally, the paper addresses the problem of performance analysis, which is crucial for analysing computational performance of the sets of coupled modules within the simulation workflow. The main contribution is the application of the extended bond graph theory for designing the structure of glue modules for integration of simulation modules. As well, the paper contributes to improve computation time required for simulation as it proposes to utilize the Bounded Analysis for finding modules being bottlenecks in complex simulation workflows. The results of this paper can be used for decomposing a simulation into several modules for physical systems. The paper also explains how this decomposition can be performance-aware. The proposed approach was validated based on three software prototypes and based on conceptual studies analysing the entire proposed methodologies. In future work, we plan to propagate the results of performance analysis back to the semantic integration of heterogeneous engineering sources automatically and to match the weak performance with the original plan data.

Acknowledgments This work was supported by the Christian Doppler Forschungsgesellschaft, the Federal Ministry of Economy, Family and Youth, and the National Foundation for Research, Technology and Development—Austria; and by the Grant Agency of the Czech Technical University in Prague, grant No. SGS12/188/OHK3/3T/13.

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Optimizing Power Consumption in Robotized Job-Shop Manufacturing

Silviu Raileanu, Florin Anton, Alexandru Iatan, Theodor Borangiu and Silvia Anton

Abstract The paper discusses the problem of power consumption optimization in flexible manufacturing cells. In today's world many companies are orienting their shop floor processes towards sustainability in order to obtain financial benefits by reducing power consumption during production (energy costs being in an ascending trend), and also for obtaining support from governmental and independent organizations programs. This study focuses on the optimization of power consumption in manufacturing processes by combining operations sequencing with resource allocation in order to obtain the minimum power consumption for a given batch of orders. The decision making algorithm relies on a decentralized system collecting data about resources' power consumption; the optimization problem is implemented using ILOG OPL.

Keywords Power consumption · Optimization · Agent-based systems

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S. Raileanu (✉) · F. Anton · T. Borangiu · S. Anton
Department of Automatic Control and Applied Informatics, University Politehnica
of Bucharest, Bucharest, Romania
e-mail: silviu.raileanu@cimr.pub.ro

F. Anton
e-mail: florin.anton@cimr.pub.ro

T. Borangiu
e-mail: theodor.borangiu@cimr.pub.ro

S. Anton
e-mail: silvia.anton@cimr.pub.ro

A. Iatan
Department of Electrical Engineering, Technical University of Civil Engineering
of Bucharest, Bucharest, Romania
e-mail: alex_iatan@yahoo.fr

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1 Introduction

Recent trends show that power consumption is a problem which is discussed and approached more often not only because of the ascending trend of energy costs but also because using and developing green solutions is encouraged by governments, European Union [1] and other bodies around the globe.

In recent years many authors have discussed this problem and proposed solutions, for example in Ref. [2] a mathematical programming model of the flow shop scheduling problem is discussed. This considers peak power load, energy consumption and associated carbon footprint in addition to cycle time in order to reduce carbon footprint. Reference [3] investigates the analytical energy modelling for the explicit relationship of machining parameters and energy consumption, resulting a model which is applied to optimize the machine setup for energy saving.

Reference [4] considers a dynamic scheduling problem which minimizes the sum of energy cost and tardiness penalty under power consumption uncertainties; in Ref. [5] a method for reducing the total energy consumption of pick-and-place manipulators for given Tool Centre Point (TCP) position profiles has been developed, and in Ref. [6] an energy consumption change forecasting system using fuzzy logic to reduce the uncertainty, inconvenience and inefficiency resulting from variations in the production factors has been proposed. Minimizing power consumption in milling and machining manufacturing processed was also approached in Refs. [7–9].

In the above mentioned papers energy monitoring is done using wattmeter devices [10] connected in the decision making infrastructure or using smart meters by measuring the energy consumption of a consumer and providing this information over a network, by employing a two way communication between the meter and the central control or supervisory system.

The novelty of the approach consists of an agent-based energy monitoring framework where resource consumption (both total energy consumed and the amount of energy consumed for each operation) is locally measured, stored and then used at a global level for allocating workload to resources using a multi-criteria optimization model. The paper is structured in six sections: in the first two the actual trend in power monitoring and optimization in manufacturing is presented; Sect. 3 describes the data acquisition system; Sect. 4 discusses the agent based model for power optimization, Sect. 5 presents the energy consumption optimization solution using ILOG OPL; the Sect. 6 reports experimental results and formulates conclusions.

2 Power Consumption

The *instantaneous power* received from the supply source is, according the power transfer theorem, the product of the instantaneous voltage $u(t) = U\sqrt{2}\sin(\omega t + \phi)$ and current $i(t) = I\sqrt{2}\sin(\omega t + \gamma)$, and is given by $p = u(t) \cdot i(t)$. By replacing the voltage and current with their expressions one obtains the instantaneous power as:

$$\begin{aligned} p &= u(t)\cdot i(t) = U\sqrt{2}\sin(\omega t+\phi)I\sqrt{2}\sin(\omega t+\gamma) = 2UI\sin(\omega t+\phi)\sin(\omega t+\gamma)\\ &= UI\left[\cos\left[(\omega t+\phi)-(\omega t+\gamma)\right]-\cos\left[(\omega t+\phi)+(\omega t+\gamma)\right]\right]\\ &= UI\left[\cos\phi-\cos(2\omega t+\phi+\gamma)\right] = UI\cos\phi - UI\cos(2\omega t+\phi+\gamma) \end{aligned} \tag{1}$$

where $\phi - \gamma = \varphi$ and $2*\sin(\alpha)*\sin(\beta) = \cos(\alpha - \beta) - \cos(\alpha + \beta)$, ω being the angular velocity, γ is the initial phase for U, φ is the initial phase for I and $\cos(\varphi)$ is the power factor.

The instantaneous power is hence a periodical value depending on the power supply voltage and the electric current in the circuit, with a constant component and a component whose frequency is twice ω; this second component is called oscillating or fluctuating power due to electric and magnetic fields produced by the circuit [11].

Of particular interest is the average value of the instantaneous power which is named the *active power* P, and is commonly referred to as the *average power*, *real power* or *true power*. This type of power is given by:

$$P = \tilde{p} = \frac{1}{nT}\int_0^T p\,dt \tag{2}$$

where P is the average value of the instantaneous power p measured for a number of full periods n.

By integrating Eq. (2) the active power can be obtained as:

$$\begin{aligned} P = \bar{p} &= \frac{1}{nT}\int_0^{nT} p\,dt = \frac{1}{nT}\int_0^{nT}[UI\cos\varphi - UI\cos(2\omega t+\phi+\gamma)]dt\\ &= UI\cos\varphi\frac{1}{nT}\int_0^{nT}dt - \frac{UI}{nT}\int_0^{nT}\cos(2\omega t+\phi+\gamma)dt\\ &= UI\cos\varphi\frac{1}{nT}t\Big|_0^{nT} + \frac{UI}{nT}\sin\left(2\omega t+\phi+\gamma\right)\Big|_0^{nT}\\ &= UI\cos\varphi\frac{1}{nT}(nT-0) + \frac{UI}{nT}\left[\sin\left(2\frac{2\pi}{T}nT+\phi+\gamma\right)-\sin\left(\phi+\gamma\right)\right]\\ &= UI\cos\varphi. \end{aligned} \tag{3}$$

The active power is the rate at which energy is expended, dissipated, or consumed by the load and is measured in units of watts [12].

This expression is null under nondissipative or purely reactive circuits and is positive for dissipative circuits. The active power can be expressed also, under single-phase pure sinusoidal conditions, using the resistance or the conductance:

$$P = UI\ \cos\varphi = RI^2 = GU^2 \tag{4}$$

where R is the electrical resistance of the receptor expressed in Ω, and G is the conductance (the inverse of the resistance), expressed in Ω^{-1}.

Equation (1) shows that the instantaneous power oscillates with the angular frequency of 2ω around its average value, which is the active power.

Even if the powered receptor (consumer) is of passive type, the active power received is always positive ($P > 0$); there are moments during a period when the instantaneous power is negative, because it is sent out of the circuit. In these moments, the energy accumulated in the magnetic field of coils or capacitors is sent back partially to the power supply.

The *apparent power* is measured in volt-amper (VA) and is defined by the product $S = UI > 0$. The apparent power can be expressed also using the impedance and the admittance:

$$S = UI = ZI^2 = YU^2 \tag{5}$$

where Z is the impedance of the circuit expressed in Ω and Y is the admittance (the inverse of impedance) expressed in Ω^{-1}.

The power factor is the positive rapport between active power and apparent power (having values between 0 and 1):

$$0 \leq k_p = \frac{P}{S} \leq 1 \tag{6}$$

In pure sinusoidal regime the power factor has the expression:

$$k_p = \cos\ \varphi \tag{7}$$

The *reactive power* is represented by $Q = UI\,\sin(\varphi) \neq 0$. The reactive power (positive in the case of inductive circuits and negative for capacitive circuits) can be expressed using the reactance and the susceptance as below:

$$Q = UI\ \sin\varphi = XI^2 = BU^2 \neq 0 \tag{8}$$

where X is the reactance of the receiver expressed in Ω and B is the susceptance (the inverse of the reactance) expressed in Ω^{-1}; in this way the reactive power is null for resistive circuits [13].

In our case, if we want to compute the energy which is paid to the supplier we will measure the instantaneous power consumption during each operation, in kW, and the time required for each operation in order to complete, in seconds. The energy is then given by:

$$Energy(\text{KWh}) = \frac{\sum\limits_{for\_each\_second} Instrantaneous\_Power}{3{,}600} Operation\_duration \tag{9}$$

3 Data Acquisition System

In order to compute the instantaneous power, which integrated over time provides the energy consumed, the instantaneous voltage and current must be measured using an acquisition board characterized by: (i) sampling frequencies above 120 Hz (double the frequency of the supply system), (ii) local processing

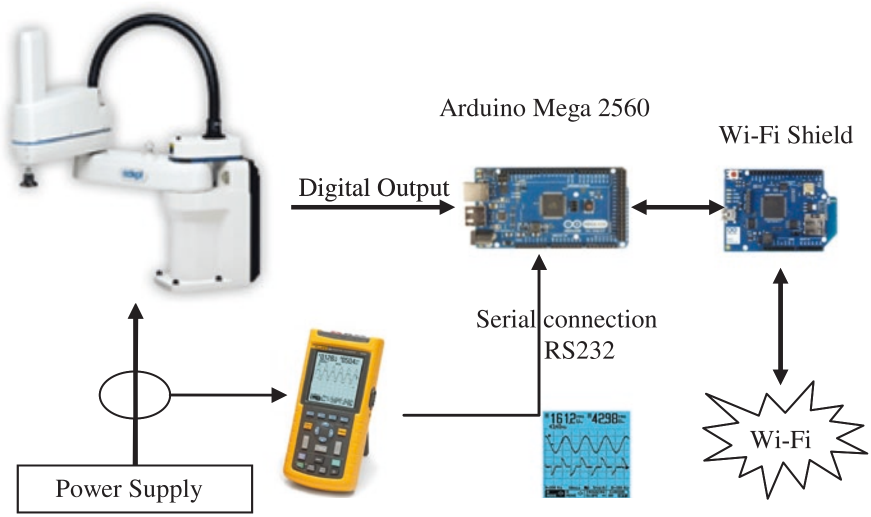

Fig. 1 Data acquisition system

capabilities and (iii) easy access to network. Taken into consideration observations i–iii and the fact that we wanted an external acquisition board which should be reused for different resources, an Atmel based platform was chosen due to its simplicity in programming and in the realization of the electronic schematic used to interface current and voltage sensors. Thus, the data acquisition system is based on an Arduino Mega 2560[1] open source electronics prototyping platform equipped with a Wi-Fi shield (required in order to communicate with other equipment in the cell), see Fig. 1.

The Wi-Fi shield is connected to a wireless router which allows data transfer between the acquisition board and the supervising system. The Arduino board is connected using a serial cable with the wattmeter (which is a Fluke 124 Industrial ScopeMeter) providing information about power consumption, voltage and current intensity every second. The Arduino board is also connected with the resource (robot) through a digital input (at the Arduino board)—output (at the robot) channel which allows synchronizing the power measurement with each robot operation.

When the robot starts a new operation the digital output signal is turned on/off for each different motion. In this way, by detecting the high-low and low-high transitions the Arduino board is able to synchronize the instantaneous power measurement with each robot operation and then transmit the data to the supervising system.

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[1] www.arduino.cc.

4 Integrating Power Consumption into the Optimization Model

The scope of this research is the design of a framework in which the energy consumed during production execution is individually collected from each workstation resource in order to predict future energy consumption and for an efficient allocation of workloads on resources. The manufacturing systems suitable for the proposed energy monitoring framework have a decentralized infrastructure consisting of multiple individual workstations containing one or more resources each of them being accessed through a single representative agent (Fig. 2), designed to offer information about: (i) the resource state, (ii) the total power consumption, (iii) the available operations and (iv) their characteristics (processing time, power consumption, quality, a.o.).

Collecting information is possible through an agentification process consisting of individual software agents associated to each workstation. These agents are responsible for decision making, activity monitoring and communication through a standard environment. In the reported research, the workstations are industrial robots which realize assembly operations. Thus, the software agent controls the physical resource (the robot manipulator) through the robot controller and processes data from the acquisition board.

The gathering, processing and integration of information about each resource is done at workstation level by the associated agent and forwarded to an entity in charge of putting together information from all resource into a centralized model used to optimize resource allocation (Fig. 2).

The collection of energy consumption for each resource in the context of production optimization and manufacturing execution has three elements (Fig. 2): (i) Data acquisition, (ii) Production planning and resource scheduling and (iii) Orders execution.

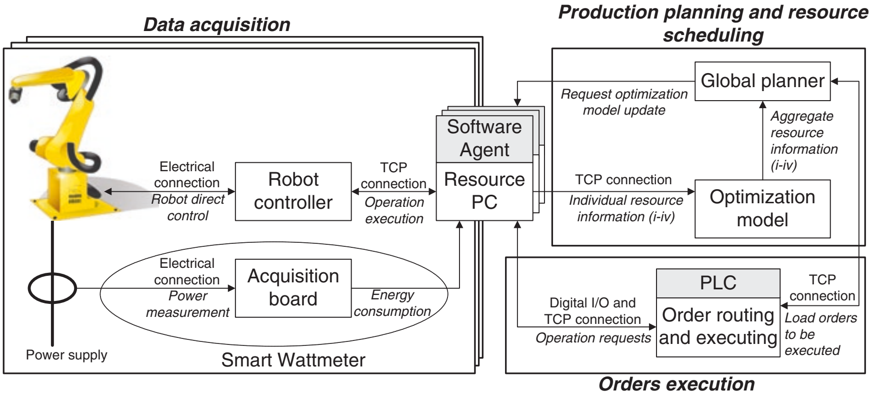

Fig. 2 Power consumption measurement and integration into the optimization model

As described before, **Data acquisition** is done individually for each workstation; the process is realized by the resource agent and has two facets (Fig. 3):

1. A continuous process in charge with instantaneous energy integration. This process is used to compute the *total energy consumption* of a resource (Fig. 3i):
   (a) The acquisition board monitors the instantaneous power consumption of the resource and sends it to the resource's agent which integrates it;
   (b) The optimization model is updated every time an operation is processed.
2. An energy consumption integration process synchronized with the operation execution. This is used to compute the *energy consumption for a given operation* (Fig. 3ii).
   (a) The Programmable Logic Controller (PLC) signals the resource agent the operation to be executed;
   (b) The resource agent executes a specified program on the physical resource. This signal is used as the start of the interval while the energy consumption for that operation will be monitored;
   (c) The termination of the operation executed by the physical resource is acknowledged to the resource agent. This confirmation is forwarded to the order agent to advance to the next operation, and is also used as a signal which updates the optimization model (the cumulated, total energy consumption of the resource and its energy consumption for each operation).

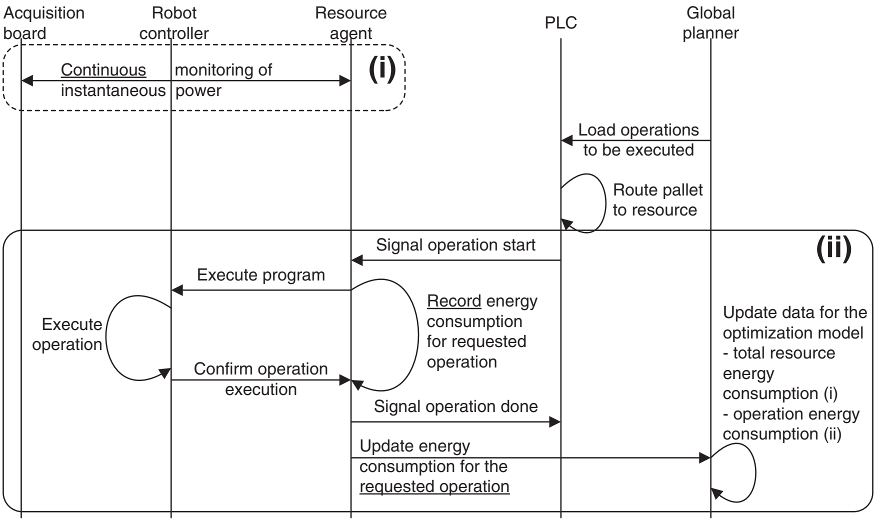

Fig. 3 Agent-based collection of energy consumption

The result of the energy collecting process described above is the total energy consumed by each resource and a data log containing the operation type, associated resource, start time, end time and energy consumed. In the global planner only the latest energy consumption for each operation will be used each time it is called.

The **Production planning and resource scheduling** module uses a request from the global planner to each resource agent to update the optimization model, followed by the answers from the resource agents and by the aggregation of this information into the optimization model used by the global planner.

The physical realization of orders with production planning and resource scheduling optimized relative to energy consumption is done through the **Orders execution** process. The planned and scheduled orders are sent by the global planner to the entity in charge of executing the production, in this case a PLC which routes the products according to their optimized schedule. The PLC's task is to associate each order with a pallet, to route the pallet towards the scheduled resource and to request the execution of the scheduled operation from the resource agent. The subsequent operation execution triggers an update of the energy consumed during the operation (Fig. 3).

5 Optimization Solution

Each workstation Pi, $1 \leq i \leq 4$ in the shop floor layout described in Fig. 4 contains one resource—a robot (P1, P2) or two resources—a robot and a machine tool (P3, P4) which can execute a set of operations characterized by different parameters. The cell features a certain flexibility meaning that some operations can be executed by different workstations, but with different energy footprints due to the fact that resources are different. In literature this type of layout is called *job-shop* [14]. The Job Shop Scheduling Problem (JSSP) has been intensely studied from the point of view of makespan minimization [15, 16]. However, from an energy minimization viewpoint considering the real-time consumption of manufacturing resources, to the best of our knowledge there have not been reported results in the literature.

Detailed scheduling problems deal with interval dimensions, start and end time of operations, sequences, resource selection, and are best tackled by constraint programming (CP) approaches.

A comprehensive list of CP solvers and libraries addressing various combinatorial problems including detailed scheduling can be found in [17]. From this list we have chosen IBM ILOG [18] because it can be easily integrated with separate applications using standard C++, C# or JAVA code through the Concert technology. It also has a powerful programming language, the Optimization Programming Language (OPL) which allows easy modelling of: precedence constraints (commands like `endBeforeStart`, `startAtEnd`, a.o.), overlapping constraints (`noOverlap`), alternative resources (`alternative`, `synchronize`) and pulse functions used for resource loading

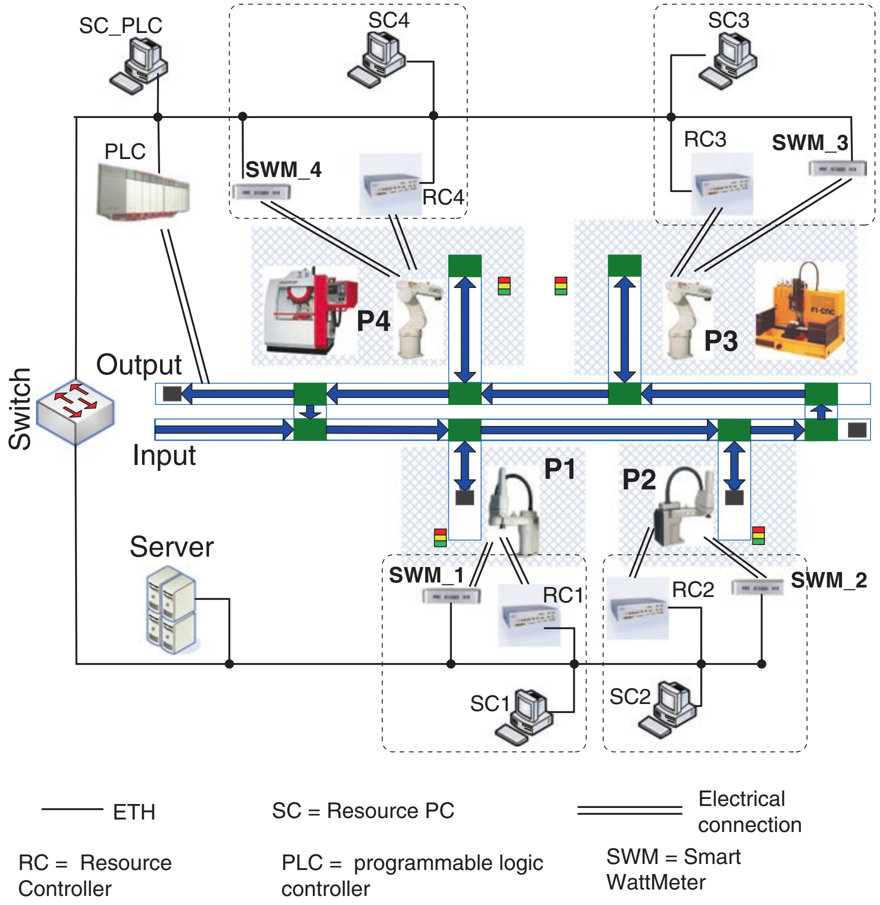

Fig. 4 Shop floor layout

constraints (`pulse`, `cumulFunction`). Other advantages include: (i) decoupling the problem model from the data, which can be loaded at runtime, and (ii) specification of a search procedure through the definition of the search tree to be explored and of the search strategy, allowing thus the reduction of runtime.

A standalone ILOG OPL optimization problem consists of a project which has at least the following components: a *model* of the problem, a *data file* used to instantiate the model and a *run configuration* which associates the model with a data file. The model is the core of the project and contains: data declaration, decision variables, the objective function, constraints, post- and pre-processing directives used to put the data in the correct format for the optimization algorithm and display the results in an understandable form.

The detailed composition of the CP model with the succession in which the components appear in the model is as follows:

- *Declaration of variables* used. These are on one hand the **operations to be executed (Ops)** and on the other hand the **modes of execution (Modes)** including processing time and energy consumed:
  `Ops = {<global operation index, local operation index, order index, precedence constraints between operations belonging to the same order>… }`
  `Modes = {<global operation index, processing machine, processing time, energy consumed>… }`
- *Decision variables* are modelled as time intervals and sequences of time intervals: intervals for executing all defined operations, intervals used by the resources to execute possible operations and a sequence of operations for each resource.
- The objective function is defined as the minimization of the energy consumed by the resources when executing a batch of orders. A detailed description of the objective function will be given in Sect. 6 (experimental results) since a simple energy minimization is not sufficient from the point of view of resource utilization (when compared with a more classical optimization criterion like makespan minimization).
- The combination of all decisions variables forms the search space. Nevertheless, not all combinations are possible; these limitations are generated by the *constraints* that the physical system is subjected to. The following constraints are defined in our case:
  - *Precedence constraints* (`endBeforeStart`) model the sequence in which operations must be executed;
  - Alternative *constraints* are used to synchronize the operation execution with a possible execution mode on a resource. The scheduling procedure consists in declaring all the possible intervals as decision variables and select only the ones that are mandatory as it results from the product definition;
  - *Overlapping constraints*: two operations should not be executed on the same resource at the same time and the number of processed orders is limited by the number of pallets existing in the system;
  - *Non-preemptive constraints*: order and operation execution are uninterruptable. This means that once an order is inserted for execution it cannot be replaced by another one until it is finished. The same statement is valid for an operation being executed on a resource.

The separation between data and model allows running the same optimization problem with different initialization data. The resource agents supply the execution times and the energy consumption to a data file for each operation executed. It is in this data file that the latest information from all resources is aggregated and further used to initialize a CP model.

The optimized solution results by executing a *running configuration*. With the above defined and initialized data the ILOG CP Optimizer uses the following technique for searching an optimized solution: (1) choose a decision variable; (2) assign a value to it; (3) reduce the search space by propagating constraints to other decision variables; (4) if step 3 fails goto 2 for a different value, otherwise goto 1. After all possibilities are tested or when another stop condition is reached (amount of time, number of infeasible solutions, a.o.) the best combination will be retained.

6 Experimental Results, Conclusions and Future Work

For the practical experiment the energy consumption and operation execution time were measured for all robot operations (an example is shown in Fig. 5 for a single operation over time) for each workstation P1–P4 (Fig. 4) using the system described in Fig. 1. The measured results, which are used for energy efficient resource allocation, are presented in Table 1.

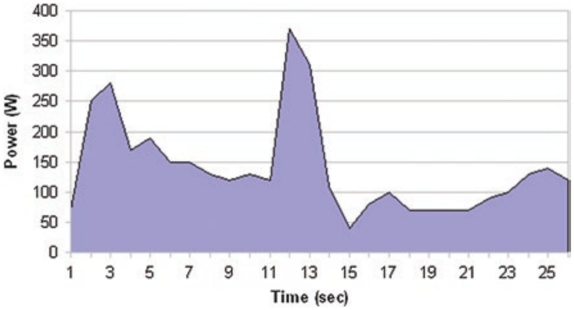

Fig. 5 Power consumption for a production operation executed by a Viper s650 vertical articulated robot

Table 1 Energy consumption and execution time for an operation

Workstation	Robot type (Adept)	Energy consumed (KWh) in continuous operation	Processing time (s)	Power consumption per operation (W)
P1	Cobra s800	4.549	26.414	33.384
P2	Cobra s600	2.450	17.029	12.014
P3	Viper s650	3.630	24.965	25.173
P4	Viper s650	3.380	21.802	20.469

Table 2 Characteristics of the optimization problem

Number of product types	5 (Prod i, $i = 1 \ldots 5$)				
Number of operations per product type	Prod1 (11op)	Prod2 (8op)	Prod3 (11op)	Prod4 (10op)	Prod5 (8op)
Number of orders	30 = 5 types of products × 6 orders for each product type				
Number of operations (Ops dimension)	$288 = (11 + 8 + 11 + 10 + 8) \times 6$				
Number of execution modes (modes dimension)	888				

The experiments have been done in the industrial manufacturing cell of the CIMR Research Centre in Bucharest,[2] the layout of which is shown in Fig. 4. The platform is composed of four workstations able to execute a wide range of operations. These operations can be either be executed on several resources (*redundant*) or executed only on a given resource (*exclusive*).

The results in Table 1 (columns 4 and 5) were used to configure the data file which instantiates the CP optimization model used by ILOG.

The ILOG-based mixed planning and scheduling model has been tested by executing a batch of 30 orders (Table 2) on the physical manufacturing structure shown in Fig. 4. The ILOG model with the characteristics presented in Table 2 was run on a machine with a Dual Core 2.6 GHz processor with 4 GB of RAM; the results of the different optimization problems are discussed.

(i) Makespan minimization (MM) characteristics:

  - Classical optimization criterion;
  - Does not take into account the energy consumed;
  - Objective function: minimize the completion time of the last executed operation (makespan);
  - Decision variables: start and end of the time intervals associated to each operation and the execution mode of each operation (which resource will execute the operation);
  - Constraints: each resource can execute a single operation and each order can receive a single operation at a given time; there is a fixed number of orders being processed at a given time; order processing is uninterruptible: once an order starts being executed it cannot be replaced by one waiting to be inserted unless another order is finished; operation execution is uninterruptible.

(ii) Energy consumption minimization (ECM) characteristics:

  - Objective function: not applicable. By choosing only the resources that consume less energy the total consumed energy will be minimized. Thus we do not deal with an optimization problem but with finding a combination which generates the minimum of a function;

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[2] www.cimr.pub.ro.

Table 3 Comparison of the three optimization modes

	Min. power (W)	Resource utilization	Makespan (s)	Power consumption (W)	Runtime (s)
(i) MM	2,928	0.98	1,301	4,787	6.2
(ii) ECM		0.12	4,461	2,928	1.2
(iii) MMEC		0.17	3,060	2,928	1.9

- Decision variables: the same as in the case of makespan minimization;
- Constraints: the same as in the case of makespan minimization plus additional constraints forcing the operations to be executed on the resources which consume the minimum energy.

If in the makespan minimization case a search space can be defined which is processed by the optimization algorithm in order to compute a solution, in the case of energy minimization the optimization problem can be reduced to finding the resources that execute an operation with the minimum energy consumption and then sequencing the needed operations on these resources. If each resource has a different energy consumption, the optimization problem is reduced to choosing only the most economical resources (from an energetic point of view) and sequencing operations on them.

As can be seen from Table 3 in the energy minimization case the consumed energy is reduced to a minimum, but the resource utilization, defined as resource working time divided by the makespan, is much smaller than in the makespan minimization case. Another drawback of the energy minimization procedure is that the resources that consume more energy are never used which results in a smaller utilization rate. Also, due to the fact that the energy minimization procedure is much simpler (find the first correct combination of intervals) than the makespan minimization procedure (analyse all the possible combinations of intervals), its execution time is smaller.

(iii) In order to improve the resource utilization the two solutions presented above have been combined into a single multi-criteria optimization problem, namely *makespan minimization with energy constraints* (MMEC), with the characteristics:

- Objective function: minimize the completion time of the last executed operation (makespan);
- Decision variables are the same as in the case of makespan minimization;
- Constraints: the same for minimization of energy consumption.

By running this problem a reduction in makespan can be observed as compared with the energy minimization technique resulting in a better resource utilization.

As a conclusion the novelty elements proposed in this paper are:

- The extension of the resource informational counterpart (resource agent) with energy consumption functionalities;
- The development of a multi-criteria optimization model combining energy consumption and makespan minimization.

The proposed control framework measures energy consumption individually for each operation executed by the manufacturing system resources. This information is processed locally by a software agent associated to each resource and forwarded to the centralized planner implemented using IBM ILOG OPL. The resulted planning and scheduling sequence is then used for executing the production orders. The advantage of this framework and its associated optimization algorithm is the real-time actualization of energy consumption used to update the CP multi-criteria optimization model. By taking into account both the time and the consumed energy an improvement of these two parameters can be observed in comparison with the situations where they are optimized separately. On the other hand a poor utilization of workstation resources can be observed in the case when there is a strict differentiation between their parameters (processing time and energy consumed).

Future research will cover the following directions: (i) Defining a *product report* containing information about its execution and energy consumption; (ii) Analyse the dependence between the energy consumption and resource utilization in order to increase the resource utilization; (iii) Creating a cost effective energy consumption monitoring system.

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Coupling Predictive Scheduling and Reactive Control in Manufacturing: State of the Art and Future Challenges

Olivier Cardin, Damien Trentesaux, André Thomas, Pierre Castagna, Thierry Berger and Hind Bril

Abstract Nowadays, industrials are seeking for models and methods that are not only able to provide efficient overall production performance, but also reactive facing a growing set of unpredicted events. One important research activity in that field focuses on holonic/multi-agent control systems that couple predictive/proactive and reactive mechanisms into agents/holons. Meanwhile, not enough attention is paid to the optimization of this coupling. The aim of this paper is to depict the main research challenges that are to be addressed before expecting a large industrial dissemination. Relying on an extensive review of the state of the art, three main challenges are highlighted: the estimation of the future performances of the system in reactive mode, the design of efficient switching strategies between predictive and reactive modes and the design of efficient synchronization mechanisms to switch back to predictive mode.

O. Cardin (✉) · P. Castagna
LUNAM Université, IUT de Nantes – Université de Nantes, IRCCyN UMR CNRS 6597
(Institut de Recherche En Communications et Cybernétique de Nantes), 2 Avenue Du Prof.
Jean Rouxel, 44475 Carquefou, France
e-mail: Olivier.Cardin@univ-nantes.fr

P. Castagna
e-mail: Pierre.Castagna@univ-nantes.fr

D. Trentesaux · T. Berger
Université Lille Nord de France, UVHC, LAMIH UMR CNRS 8201,
59313 Valenciennes, France
e-mail: Damien.Trentesaux@univ-valenciennes.fr

T. Berger
e-mail: Thierry.Berger@univ-valenciennes.fr

A. Thomas · H. Bril
Research Centre for Automatic Control (CRAN), CNRS (UMR 7029), Nancy University,
ENSTIB, 27 Rue Philippe Seguin, 88000 Epinal, France
e-mail: Andre.Thomas@univ-lorraine.fr

H. Bril
e-mail: Hind.Bril@univ-lorraine.fr

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Keywords Holonic control · Predictive/reactive · Performance indicator of the production system · Discrete-event observer · Flexible manufacturing system

1 Introduction

Classical (historical) predictive approaches consist in using a centralized predictive scheduling system loosely coupled with a reactive control system that implements it. The scheduling models are based on mathematical representation of the production system from which an optimization or heuristic algorithm is designed and computed in a centralized way. This approach leads to determine or approximate the optimal sequence of tasks to be executed in the system in order to maximize one or several criterion (criteria) somehow related to productivity, customer satisfaction, etc. The result of the calculation is then used by the Manufacturing Execution System (MES) for the Production Activity Control of the production system [1]. This approach is considered optimal as long as the modelling of the production system is realistic but also deterministic. In such an approach, parameters are simplified in order to fasten up the calculations. If stochastic changes of parameters are significant (e.g. duration of manual operations, breakdowns or failures), the execution of the schedule in the production system gives results that are generally far from optimal or even inapplicable [2]. Traditionally, the production system is halted at the time when a disruption is detected during the execution of the scheduler then waits for a new schedule to be generated. If the rescheduling phase is long or if disruptions happen frequently, the duration of the rescheduling phase may lead to a drastic reduction of the overall performance. As a consequence, this approach, despite the fact that it has been widely used for several years in a number of industries, cannot be considered as sufficiently efficient nowadays since reactivity issues grow more and more important. Since few years, a research field, dealing with proactive scheduling has emerged. The main idea is to increase the robustness of the predictive schedule, and as a consequence, to limit the “nervousness” of the scheduling/rescheduling iterations, see for example [3]. These techniques typically use redundancy (temporal or resource-oriented), probabilistic methods, contingent methods, or objective functions that integrate robustness criteria evaluating the risk to not respect a candidate scheduling given possible perturbations. A growing activity from operation research has emerged in the last few years in that field [4].

Reactive approaches consider every event in real time, with no anticipation. Several approaches can be identified depending on the fact that they are centralized or distributed. When centralized, priority rules (e.g. heuristics-based) are defined and used on the fly, that is, whenever a decision must be taken. The choice of the rule to apply can also be decided dynamically. When distributed, control decisions are distributed among a set of cooperative control entities, being agents or holons with no hierarchical relationships among them. Distributed approaches have been studied by researchers massively in the 90s, see for example [5], one of the historical reference in this field. These approaches are known to generate applicable solutions since decisions are taken according to the real state of the production system. Despite this, they are also known to have their performances rapidly decreasing with time compared to pure predictive ones if no perturbation occurs.

Due to the limitations of these two historical approaches facing the current industrial needs, researchers are more and more considering a last kind of approach by trying to propose scheduling and control architectures and models that couple local reactive mechanisms implemented into agents/holons with global predictive mechanisms, being robust or not. In such predictive/reactive or proactive/reactive approaches (denoted hybrid approaches in the sequel of this paper), some of these control holons/agents are typically interfaced with the predictive scheduling system that provides them with an optimal or approximated scheduling and, at the same time, interfaced with components like physical products or resources of the physical production system to control them [6, 7].

In such hybrid architectures, the fundamental decision facing perturbation is whether to still follow the predictive/proactive schedule (predictive mode) or not. If not, they may switch to a reactive mode where events and decision are handled in real time with the intention to switch back to a predictive mode as soon as possible. The main issue for researchers is then to provide accurate mechanisms to define the best switching dates (and/or the best switching decision-making levels) to control holons/agents so that they behave in such way that the whole behaviour of the hybrid architecture stays globally optimized despite disturbances. This predictive/proactive-reactive coupling issue is not easy to solve: for example, if a broken machine can be repaired quickly, then it may not be necessary for its control holon/agent to switch in reactive mode if the pre-determined schedule will be still accurate because of some slack in the original schedule. Another issue is related to the possible nervousness of the architecture that may often switch from one mode to another [8].

From our point of view, this global issue can be broken down into the following scientific challenges. First, it is necessary to provide tools that enable the estimation of future performances, including disturbance detection, diagnosis and prognostic mechanisms (i.e. evaluation of the impact of a disturbance on the global performances). Second, based on these estimators, it is necessary to design efficient synchronization mechanisms, leading typically to the design of a proper indicator to determine if necessary when it is pertinent to switch back to predictive mode. Third, efficient switching strategies based on these synchronization mechanisms must be designed. These strategies must lead to a fair use of reactive modes (sufficiently to absorb uncertainties, but used as less as possible to avoid decreasing the performance). These strategies must be integrated into a control system considering balanced articulation between hierarchical mechanisms and heterarchical ones, while avoiding nervousness. The following sections propose a literature review structured following these three underlined challenges in the context of hybrid architectures.

2 First Challenge: Estimation of Future Performances

One fundamental reason explaining the lack of studies devoted to the predictive/proactive-reactive coupling issue in hybrid architectures, is related to the difficulty for researchers to design models enabling them to estimate future performances because of the difficulty to accurately observe the real state of the production system (e.g., locate products and their state), and extrapolate possible evolution scenarios in the near future. This feature is mandatory in order to detect at which moment the control should switch from a predictive to a reactive mode. This detection might only be based on prediction models, split into two classes: analytic models, rapidly limited by the size of the considered systems because of their algorithmic complexity, and discrete-event simulation models, able to handle large systems but extremely time-consuming. This last characteristic often limits their use in the context of real-time decision making.

To solve this issue, an observer able to detect abnormal behaviour (difference between theoretical expected behaviour and observed behaviour—state reconstruction abilities) and to evaluate the impact of this difference on the global behaviour of the system (diagnosis abilities) must be designed [9]. For example, if it is obviously necessary to detect the delay in execution of a task from the predictive schedule, some of these delays might not be critical for the behaviour of the system, either because they are very short, or thanks to the available free margin. Many modelling formalisms are classically used to build diagnosers, including automata [10] and their timed and probabilistic extensions, Petri nets [11, 12], state charts and hierarchical state machines [13]. The most promising perspective here would be to implement the diagnoser using online simulation, which is an efficient but hard to implement forecasting tool. These programs are usually dedicated to the dimensioning phase (offline), but are increasingly used as actual systems control tools, included in the control loop (online) [14].

3 Second Challenge: Designing Efficient Synchronization Mechanisms

The “switch down” mechanism consists in switching from a predictive mode where a predictive scheduling is to be executed by holons to a reactive mode where real-time holon decision may override these predictive scheduling decisions. This kind of switching is widely addressed in the literature (event-driven or threshold-driven switch), see for example [7]. But a first issue appears: researchers do not really pay attention to the real need to “switch down” (e.g. if a machine breakdown is shortly repaired, then slack may be used to avoid real-time overriding decisions).

In addition, the “switch back” mechanism that concerns the way the predictive mode is reused after and instead of the reactive mode, is rarely addressed or even mentioned. All these decisions must be taken according to global performances objectives targeted by the production manager. To correctly address this challenge, two questions relevant to synchronization have first to be answered to:

- What are the most pertinent criteria to switch down or back?
- How to reinsert these concerned in-progress products in the remaining of the material flow (the switch down case), or how to synchronize the new re-optimized schedule with the state of the manufacturing system after this optimized schedule is obtained (the switch back case)?

The first question is relative to performance indicators system leading to be able to estimate when it is pertinent to switch down or back according to the circumstances (the physical context: flexible manufacturing system, shop floor, constraints, management rules, etc…). It is obvious that objectives and performance indicators must be determined according to the industrial context and it seems difficult to design generic indicators useful (and applicable) to a particular system. They have probably to be design according to the physical context or at least according to an industrial system class.

Indicator system according to the class of physical context and built on a learning system might be pertinent. Multicriteria optimization based on Choquet integrals could, according to the estimators obtained thanks to the first challenge, lead to establish switching points according to measured drifts and situations. This approach is close to the one proposed by Chan et al. [15]. The authors proposed an integrated approach for the automatic design of flexible manufacturing systems using simulation and multi-criteria decision-making techniques. In this work, the selection of the most suitable design, based on a multi-criteria decision-making technique, the Analytic Hierarchy Process (AHP), is employed to analyse the output from the flexible manufacturing system simulation models. Intelligent tools such as expert systems, fuzzy systems and neural networks, were developed to support the design process of the flexible manufacturing system.

Muhl [16] proposed for the automotive industry a way to optimize, in a centralized way, the schedule of the car assembly line according to a unique performance indicator and the determination of the pertinent parameters which were periodically recalculated to assure the best synchronization between the real shop-floor state and the new schedule. Another way to design this indicator system could be found thanks to learning mechanisms as neural networks, fuzzy approaches or Choquet integrals usage [17]. During his PhD work, Herrera [6, 18] first merged the two centralized and distributed approaches applied to a similar industrial case. He proposed a multi-level parametric model to solve this re-scheduling problem. But the performance indicator leading to the switch decision has been taken as a hypothesis and the distributed decisions were limited to the first choice with a simple splitting decision to reinsert the remaining parts in the existing predictive schedule. Another research work focusing on the synchronization problem was done by El Haouzi et al. [19]. She proposed an original architecture to control manufacturing flows on two assembly lines. In case of disturbances, products can arrive early or late at the synchronization point between the main assembly line and its feeders. The architecture was composed of an ERP and a distributed decision system. The on-line information was provided by Auto-ID technologies.

4 Third Challenge: Designing Efficient Switching Strategies Integrated into a Hybrid Control Architecture

Several European projects addressed the designing of distributed/hybrid control architectures into the so-called "smart factories". PABADIS and PABADIS PROMISE are amongst the firsts EU projects in that direction. More recently, let's mention GRACE, SMARTPRODUCT and ARUM projects.[1] The GRACE project is in line with the current need to build modular, intelligent and distributed manufacturing control systems and studied more precisely the impact of manufacturing operation on quality. The distributed control architecture is interfaced with a Manufacturing Execution System (MES). The SMARTPRODUCT project focused the work on the embedding of "proactive knowledge" into smart products. "Proactive" Smart products "talk", "guide", and "assist" designers, workers and consumers dealing with them. Some proactive knowledge will be co-constructed with the product, while other parts are gathered during the product lifecycle using embedded sensing and communication. Neither GRACE nor SMARTPRODUCT addressed the optimization of the control architecture, being hybrid or not. More recently, an interesting initiative, the ARUM project, aimed at designing a holonic multi-agent system combined with a service architecture designed to improve performance and scalability beyond the state of the art. The proposed solution integrates multiple layers of sensors, legacy systems and agent-based tools for beneficial services like learning, quality, and risk and cost management, including ecological footprints aspects.

In the scientific literature, there also exist different hybrid scheduling and control architectures. Pach et al. [7] pointed out that the main idea is to take advantages of two basic structuration mechanisms: hierarchical (vertical relationships, toward centralization of information and decisions) and heterarchical (horizontal relationships, towards distribution of information and decisions) mechanisms. By doing this, it is expected to avoid their respective drawbacks (typically: lack of reactivity for hierarchies and myopia for heterarchy). Thus, usually, the hierarchical part of the architecture is responsible for the predictive and global optimization, while the heterarchical part allows reactivity and local optimization. Famous flagship hybrid architectures are ADACOR [20], PROSA [21] or D-MAS [22]. Such hybrid architectures are composed of cooperative decisional control entities, typically modelled as holons or agents. In [7] an original literature review of several hybrid architectures was proposed. Indeed, there

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[1] http://grace-project.org/, http://www.smartproducts-project.eu/ and http://arum-project.eu/.

are numerous ways to combine the introduced structuration mechanisms. The authors identified two lines of study. The first "**structure dynamics**" concerns the possibility of the control structure to evolve with time (dynamic structure, e.g. full change from pure hierarchical to a pure heterarchical architecture) or not (static structure). The second "**control homogeneity**" deals with the way the control is applied: in the same way for every decisional agent/holon (homogeneous control) or not (heterogeneous control). In terms of structure dynamics and homogeneity control, hybrid architectures have thus been positioned according four sub-classes.

Non static hybrid architectures are very promising since they provide (self-) adaptation mechanisms needed to improve the agility of the control system [8]. In such architectures, an important mechanism of switching is responsible to switch holons/agents from/to predictive to/from reactive modes (for a holon/ agent or a group of holons/agents). This mechanism adapts dynamically the structure of the control architecture to the production uncertainties in ensuring the performance. Of course, more generally, there may be different intermediary levels and mode between a fully predictive and a fully reactive mode. As a consequence, attention must be paid when designing and optimizing hybrid architectures. Some first ideas have been proposed in [7], but they were provided aside the main topic of the referenced paper. Thus, this initial work was clearly insufficient and not really formalized in a generic and effective way. For example, the production order set was assumed to be provided as a whole, in a static manner, with no "on the fly" orders. Under that condition, the switching down was made only once, and with low attention paid to the real need to switch down. Moreover, the switch back was made only at the end of the production of the order set.

This challenge is complex to address and despite the growing number hybrid architectures proposed in the literature, the way prediction and reaction are coupled is neither optimized nor even clearly justified. This contributes clearly to a lack of applications of such contributions in real situations in industries despite the fact that they respond to a real industrial need. As an illustration, to the best of our knowledge, only P2000+ [23] was applied in Daimler but it failed because of issues related to the proposed research topic (and others issues, such as global cost).

5 Conclusion and Perspectives

This paper depicted a state of the art of predictive-reactive control architectures of manufacturing systems. Even though these hybrid architectures show promising performances on academic examples, three main challenges are still to be investigated from the authors' perspective. Several leads are given to orient future research activities in this field, with the objective of making these concepts applicable on industrial shop floors in the next few years.

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Application of Holonic Paradigm to Hybrid Processes: Case of a Water Treatment Process

Carlos Indriago, Olivier Cardin, Naly Rakoto, Edgar Chacón and Pierre Castagna

Abstract The holonic paradigm has been widely studied in the context of manufacturing. These productions are discrete type because operations included do not involve continuous evolution variables. A different system class is studied here—hybrid system, which includes systems with piecewise continuous evolution and whose changes are related to the evolution of discrete variables. In this case, a reconfiguration of the system is usually necessary, and holonic paradigm is an appropriate response to the need for flexibility arising. This paper proposes an adaptation of holonic reference architecture on a hybrid system case. The proposed model is composed of the union of the hybrid model and the holonic model, where the proposed controller is represented by the product holon and the order holon, the interface is represented by the logical part of the resource holon, and finally the production system is represented by the physical part of the resource holon. A case study based on a water treatment process is investigated to demonstrate the applicability of PROSA based concepts to a hybrid system.

Keywords Holonic manufacturing systems · Hybrid systems · PROSA · Water treatment process

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C. Indriago · O. Cardin (✉) · N. Rakoto · E. Chacón · P. Castagna
LUNAM Université, IUT de Nantes—Université de Nantes, IRCCyN UMR CNRS 6597,
Institut de Recherche en Communications et Cybernétique de Nantes, 2 avenue du Prof. Jean Rouxel, 44475 Carquefou, France
e-mail: Olivier.Cardin@univ-nantes.fr

C. Indriago
e-mail: Carlos.Indriago@univ-nantes.fr

N. Rakoto
e-mail: Naly.Rakoto@mines-nantes.fr

E. Chacón
e-mail: echacon@ula.ve

P. Castagna
e-mail: Pierre.Castagna@univ-nantes.fr

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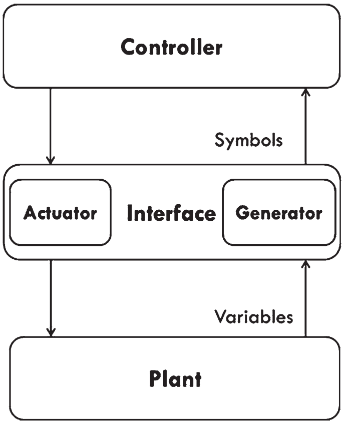
1 Introduction

In production systems there are discrete processes, where the individual parts are produced using various discrete loosely coupled operations such as machining, drilling, grinding etc.; then these parts are placed together in an assembly line to create the main end-product. On the other side, there are continuous processes that involve continuous flow of materials (such as Bulk chemicals) and utilities through process units interconnected via piping streams. Between the discrete systems and continuous systems, there are systems called semi-continuous class of processes, which, similarly to continuous processes, also involve continuous flow of materials and utilities but are not operated with a purely steady-state mode. Semi-continuous processes are particularly important in this work, specifically systems called "dynamic hybrid systems". According to Koutsoukos et al. [1], such a system consists of three distinct levels (Fig. 1). The controller is a discrete-state system, a sequential machine, seen as a Discrete Event System (DES). The controller receives, manipulates and outputs events represented by symbols. The plant is a continuous-state system typically modelled by differential equations; it is the system to be controlled by the discrete-state controller. The plant receives, manipulates and outputs signals represented by real variables that are typically (piecewise) continuous. The controller and the plant communicate via the interface that translates plant outputs into symbols for the controller to use, and controller output symbols into command signals for the plant input. The interface can be seen as consisting of two subsystems: the generator that senses the plant outputs and generates symbols representing plant events, and the actuator that translates the controller symbolic commands into piecewise constant plant input signals. Hybrid systems are conventionally modelled by switching patterns using the whole system instead of atomic resource. Therefore, the reconfiguration process is complex because it must take into account the system as a whole. Hence, there is need to find new architectures for these hybrid systems in order to improve their flexibility and reconfigurability.

Fig. 1 Hybrid systems architecture



It is well known that holonic architectures [2–4] are flexible architectures which allow online reconfiguration of processes. A holonic manufacturing architecture shall enable easy (self-) configuration, easy extension and modification of the system, and allow more flexibility and a larger decision space for higher control levels. The structure of the PROSA reference architecture is built around three types of basic holons: order holons, product holons, and resource holons. Each of them is responsible for one aspect of manufacturing control, be it logistics, technological planning, or resource capabilities respectively. Although there are other holonic architectures, PROSA presents the advantage of being more conceptual, and therefore less application dependent than the others, specifically made for discrete-event manufacturing systems. Even if holonic architectures were designed for discrete manufacturing systems, some authors have proposed the use of holonic models for continuous systems [5–7]. However, all these works develop specific architectures, and do not consider the implementation of conventional holonic systems like PROSA on hybrid systems. The objective of this paper is to demonstrate the possibility of using PROSA to model a hybrid system. The paper is based on modelling a case study of hybrid systems, namely “water treatment process”, initially proposed by Villa et al. [8].

In chapter Optimizing Power Consumption in Robotized Job-Shop Manufacturing the state of the art of holonic modeling of hybrid systems is provided. Then an explanation of the case study is carried out in chapter Coupling Predictive Scheduling and Reactive Control in Manufacturing: State of the Art and Future Challenges, and this chapter develops the holonic modeling of the water factory.

2 State of the Art

The application of holonic systems on continuous systems has been studied by several authors. An implementation of holonic production system on a continuous system is proposed by McFarlane [5]. The framework showed in Fig. 2 internally converts goals or requirements into an allowable set of parameters or trajectories of behaviour via some form of decision function, D. The actual control action is then carried out in process P. The terminology in Fig. 2 is as follows:

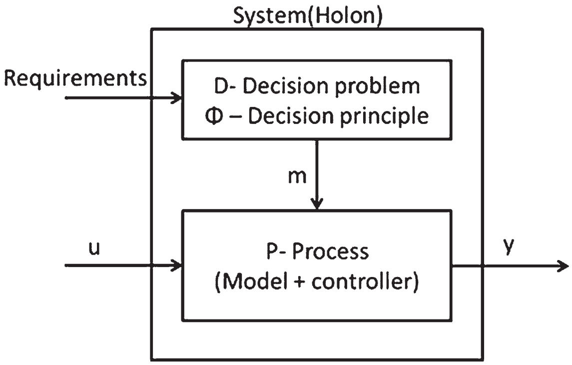


Fig. 2 Control framework for HMS

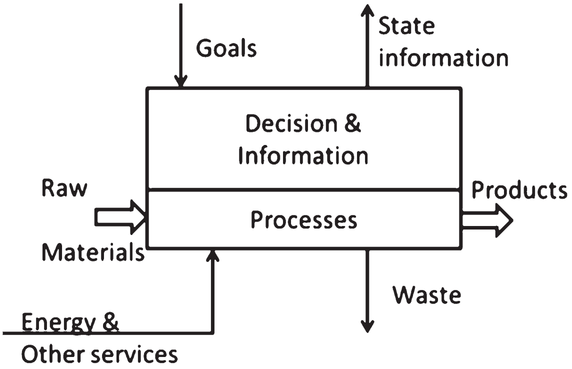
- P: process (model + controller);
- D: decision problem;
- Φ: decision principle;
- m: set of alternate decisions;
- u: set of alternate events;
- y: set of possible outcomes;

where $m \in M, u \in U, y \in Y, P : M \times U \rightarrow Y$.

The development of appropriate (and flexible) decision problems is the key to embedding control activity within holonic systems whose goals may differ depending on the environment that they operate in. It is clear from the test cases that a distributed optimization based decision principle is well suited to holonic systems, and the goal-seeking methods could help with the integration of complex optimization based control algorithms into manufacturing operations—a relatively uncommon event at present. Another holonic architecture developed for continuous systems is that proposed by Chacón et al. [6]. It proposes a holonic structure based on a decision making system called production unit (Fig. 3). This unit is the foundation for exploiting the fractal structure characteristic of holonic systems. The aggregation of production units is then called complex production system.

The production unit has physical (raw materials, finished goods, services) and logical (goals, state information) inputs and outputs. In addition, this production unit follows a holonic structure composed of three bases holon called resource holon, mission-product holon and engineering holon. Finally, the work developed by Chokshi and McFarlane [7] shows an approach to distributed coordination process for reconfigurable control. In this work, a control architecture is developed using four basic elements such as the *product element*, the *unit element*, the *header* and the *service element*. Although it does not explicitly address the holonic paradigm, the goal of this architecture is to have a control system based on reconfigurable and flexible interaction models, similar to holonic systems and it can be implemented in continuous and semi-continuous processes.

Fig. 3 Production unit



3 Case Study

The studied process is the drinking water treatment plant of Bogota (Colombia), at an altitude of 2,800 m. The plant uses 16 filters in a parallel configuration treating on average a flow rate of 12 m^3/s. The volume of water produced by this plant covers up to 60 % of consumption of Bogota city. This plant has two water sources, Chingaza and San Rafael which can provide a flow rate of 22 m^3/s.

Production of drinking water is achieved through physical, chemical, and biological processes that transform inlet source water to drinking water. However, inlet water quality is highly variable by natural perturbations and/or occasional pollution. A simplified diagram of water treatment plant is presented in Fig. 4. Input variables are pH, turbidity, alkalinity, colour and volume of inlet water. Key steps in treatment process are coagulation, flocculation, filtration, pH correction and bacterial correction.

This water treatment plant is classified into direct in-line filtration because the flocculation occurs in the filter itself. The operation of direct filtration is of lower time with respect to conventional treatment plants, and automatic tuning of the coagulant dosage is highly desirable. The case study is focused on the removing-turbidity sub-process. The inlet water is mixed with chemical coagulant additive used for accelerating the aggregation of particles, the aggregated particles of appropriated size stay seized in the filters. Interaction between chemical coagulant and suspension particles in water can be measured by ionic potential caused by charged particles motion, because it is a measure of charged particles neutralization. This potential is named Z potential. The on-line measurement of Z potential is difficult; however it is possible to measure a related variable named Streaming Current (SC), that is the current caused by superficial ions of suspension particles

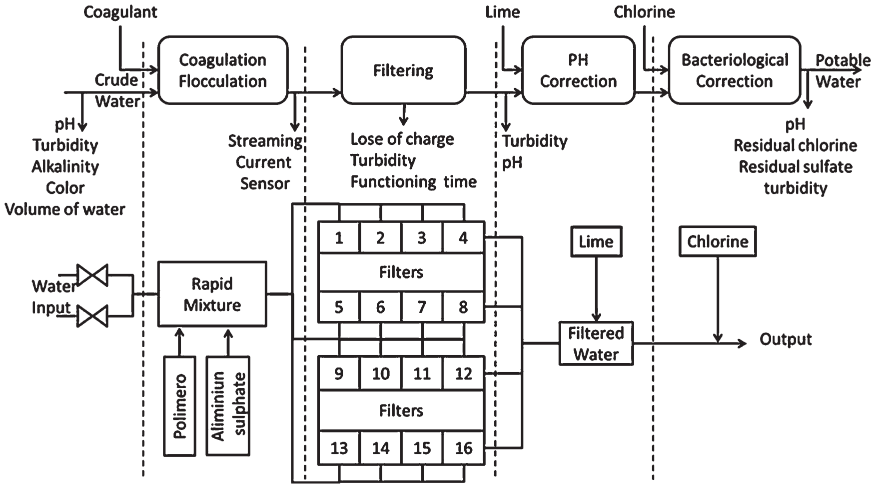


Fig. 4 Simplified diagram of the water treatment process

and there exists a direct relationship between SC and Z potential. The filtration mechanism is composed of several and complex physical phenomena and a universally accepted model is not available. Each filter has two measured variables: head loss (HL) and outlet water turbidity (T_). Head loss represents the difference of the pressure between surface of highest bed and lower surface of lowest bed of the filter. The head loss occurs when water flows pass through a bed of filter and the particles with a given size stay in the interstitial spaces of the bed. The volume of water capacity of filters becomes lower, as normally the filters are operated at a constant rate. Thus, the pressure of inlet water has to be increased. Head loss increases with the operation time, and volume of water treated.

Outlet water turbidity of each filter is a measure of filter efficiency and a function of head loss and size of suspension particles. If the size of suspension particles is big enough, they stay in the filter; otherwise, the particles with small size will pass the filter with the outlet water. Therefore, if the head loss increases, the interaction forces between filter material and retained particles are broken and turbidity increases too. When the head loss or turbidity reaches a predetermined threshold or when the maximal operation time is reached, the filter has to go into a backwashing process. Using this general description of the process the following components can be extracted:

- *Continuous variables*: influent turbidity, pH, streaming current, volume of water, loss of charge (LC) and effluent turbidity (TF).
- *Discrete Variables*: water source (op), backwashing (BW) operation, operation time. A state transition diagram of water treatment plant operation is shown in Fig. 5, extracted from the modelling of the system presented in [8].

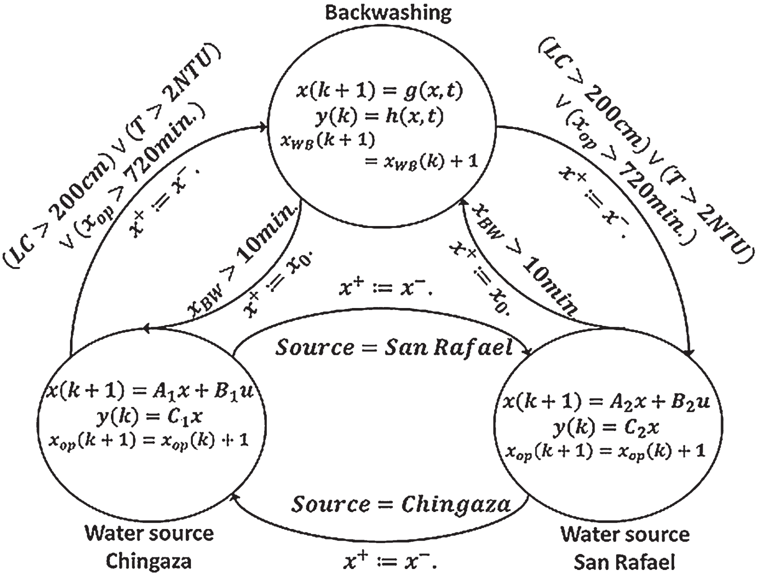


Fig. 5 State transition diagram of water treatment plant operation

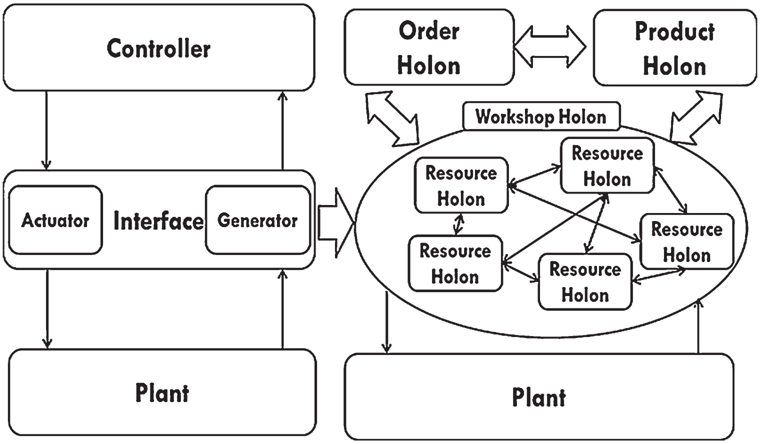


Fig. 6 Holonic architecture of a hybrid system

- *Controlled switching*: each water source represents a different behaviour of the continuous variables: streaming current, effluent turbidity and head loss.
- *Autonomous Jumps*: each backwashing operation re-initializes the continuous variables associated to the filter: effluent turbidity, head loss and operation time.

4 Holonic Modelling

Figure 6 illustrates the transition of conventional hybrid systems into the holonic paradigm of model system. Hybrid control architectures are composed of three parts: controller, interface and plant. In this holonic hybrid system model, the controller is represented by product and order holons, the interface is by the logical part of the resource holons and the production system by the physical part of the resource holons.

4.1 Product Holon

According to PROSA [2], in discrete event systems the product holon contains knowledge of the process and product to ensure the correct performance of the product with sufficient quality.

In hybrid context, a service-oriented specification as proposed in [9] is well suited for the product specification. The distinction made in this article with respect to the definition used in [9] is that the parameters and variables of the service can be continuous or discrete. In our case study, the product holon is related to the drinking water, characterized by quality requirements. The quality levels are measured on the system using pH, residual chlorine, residual sulfate and turbidity sensors. Using the definition of parameterizable services, general product recipes can be created. Two cases may appear: on cases like the one presented here, a single general recipes is defined, with flexibility granted on parameters definition in order to cope with the water quality evolution along time. The parameters that parameterize services here are: aluminium sulfate amount, chlorine amount and lime amount. On other cases, several general recipes may be defined, in order to illustrate the possibility to modify the order of the services application to the product. In this configuration, the product holon is in charge of the instantiation of the general recipe using the available resources in order to cope with the quality requirements.

4.2 *Resource Holon*

The resource holon is composed by a physical part and a logical part. The physical part is represented by the plant, and in our case study is divided into five holons (Fig. 7): the input switching system (2 valves), the Aluminium sulfate injection system (11 tanks and 10 pumps) the filtering and backwashing system (16 filters, 2 tanks and 5 bombs), the lime injection system (1 silo, 2 heaters, 2 outrigger and 3 pumps) and the chlorine injection system (10 scales, 4 evaporators, 5 chlorinators and 18 valves). Each system contains enough elements for establishing switching control policy, so that each system has hybrid behaviour. The logical part of the resource holon is an abstraction of the physical part and contains the conversion models from continuous states to discrete states and vice versa. The models used are hybrid Petri nets that change their state using threshold levels of continuous

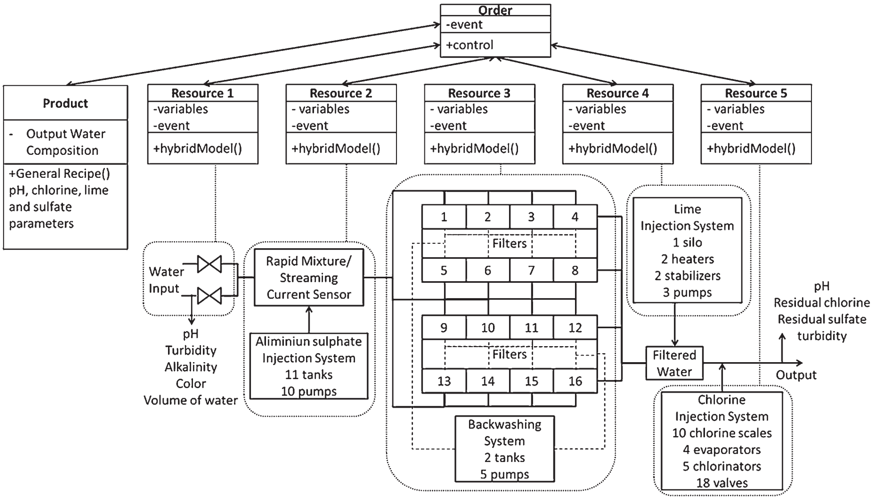


Fig. 7 Simplified diagram of the water treatment process

variables (pH, SC, turbidity). Several models can coexist in the resource holon and represent features such as fault detection model, the desired behaviour model and models that are inherent in holonic paradigm as a negotiation model for example.

One of the main features of the resources is to be able to compute the optimal parameters set in order to fit the requirements of the holarchy. Therefore, the resources are fractally decomposed into sub resources, able to negotiate with one another, until reaching the lowest level of resources, where it is possible to define the optimal set of parameters using differential equation solving.

4.3 Order Holon

The function and structure of order holons remain the same as in PROSA. Indeed, the architecture proposed in this paper guarantees that all information and models to be manipulated by the order holon are discrete or discretized. The discretization process of control variables is conventionally used in the control of hybrid systems; the difference with our proposition is that the behaviour model of each holon is simpler than the overall behaviour model of the hybrid system, and therefore easier to discretize. In our case study, the order holon has the responsibility for controlling the amount of water to be treated and the resource coordination to ensure the product quality establishing the goals to achieve for each resource holon. When a new order is placed, the associated product holon computes the best recipe and the best set of parameters to be used in order to optimize the production. This evaluation might be repeated when a severe disruption occurs and modifies the expected performance of the system. Sub-order holons are also created to assign production goals to resources, goals that they shall propagate to sub resources with the creation of new sub-order holons.

5 Conclusion

The work proposed in this paper concerns the implementation of a holonic architecture for hybrid systems. The model presented tends to confirm the good fit of the classical reference architecture PROSA to this class of systems. The holonic architecture also provides its intrinsic simplicity, simplest management models behaviour and flexibility, with the possibility to reconfigure resources online.

Therefore, further work will cover aspects of resource planning and fault tolerance models and propose new adaptation of other holonic reference architectures such as ADACOR or HCBA.

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Implementation of an Erlang-Based Resource Holon for a Holonic Manufacturing Cell

Karel Kruger and Anton Basson

Abstract The use of holonic control in reconfigurable manufacturing systems holds great advantages, such as reduction in complexity and cost, along with increased maintainability and reliability. This paper presents an implementation of holonic control using Erlang, a functional programming language. The paper shows how the functional components of a PROSA resource holon can be implemented through Erlang processes. The subjection of a case study implementation to a reconfigurability experiment is also discussed.

Keywords Erlang/OTP · Holonic manufacturing systems · Reconfigurable manufacturing systems · Manufacturing execution systems · Automation

1 Introduction

Reconfigurable Manufacturing Systems (RMSs) are aimed at addressing the needs of modern manufacturing, which include [1]: short lead times for the introduction of new products into the system, the ability to produce a larger number of product variants, and the ability to handle fluctuating production volumes and low product prices.

RMSs then aim to switch between members of a particular family of products, by adding or removing functional elements, with minimal delay and effort [2, 3]. For achieving this goal, RMSs should be characterized by [4, 5]: modularity of system components, integrability with other technologies, convertibility to other products, diagnosability of system errors, customizability for specific applications, and scalability of system capacity. RMSs thus have the ability to reconfigure hardware and control resources to rapidly adjust the production capacity and functionality in response to sudden changes [1, 6].

K. Kruger · A. Basson (✉)
Department of Mechanical and Mechatronic Engineering, Stellenbosch University,
Stellenbosch 7600, South Africa
e-mail: ahb@sun.ac.za

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A popular approach for enabling control reconfiguration in RMSs is the idea of holonic control. Holons are “any component of a complex system that, even when contributing to the function of the system as a whole, demonstrates autonomous, stable and self-contained behaviour or function” [7]. Applied to manufacturing systems, a holon is an autonomous and cooperative building block for transforming, transporting, storing or validating information of physical objects.

Several experimental implementations of holonic control have been done using agent-based programming (such as in [8]), often using JADE as development tool. From our experiences with JADE, we believe there is room for improvement concerning complexity, industry acceptance, robustness and scalability.

This paper describes the implementation of holonic control using Erlang. Erlang is a functional programming language developed for programming concurrent, scalable and distributed systems [9]. The Erlang programming environment is supplemented by the Open Telecommunications Platform (OTP)—a set of robust Erlang libraries and design principles providing middle-ware to develop Erlang systems [10].

Erlang has the potential to narrow the gap between academic research and industrial implementation. This is due to several advantages offered by the Erlang language, such as increased productivity, reliability, maintainability and adaptability.

This paper describes an Erlang-based implementation of the control component for a PROSA resource holon in a reconfigurable manufacturing cell, focusing on:

- The functional components of a resource holon which must be incorporated by the Erlang implementation (Sect. 2)
- A case study which demonstrates the Erlang-based holonic control (Sect. 2)
- The implementation of the functional components of resource holon control through Erlang/OTP processes (Sect. 4)
- The reconfigurability of the resource holon in reaction to changes in the holon’s service specification (Sect. 5).

2 Case Study

The case study chosen for the presented Erlang-based holonic control implementation, as shown in Fig. 1, entails the testing of circuit breakers. The station utilizes a pick-‘n-place robot to move circuit breakers from an incoming fixture to specified tester slots, in a specified sequence. Upon completion of the testing, the robot removes the circuit breakers and places them in the outgoing fixture. Breakers on the same fixture may require testing in different tester slots, which differ in testing parameters and times.

The robot utilized in the case study is a Kuka KR16 robot, fitted with two pneumatic grippers at the end effector (only one of the grippers is used in this implementation). A mock testing rack with four tester slots is used—the slots are fitted with a spring-loaded clamp to hold the breakers in place during testing.

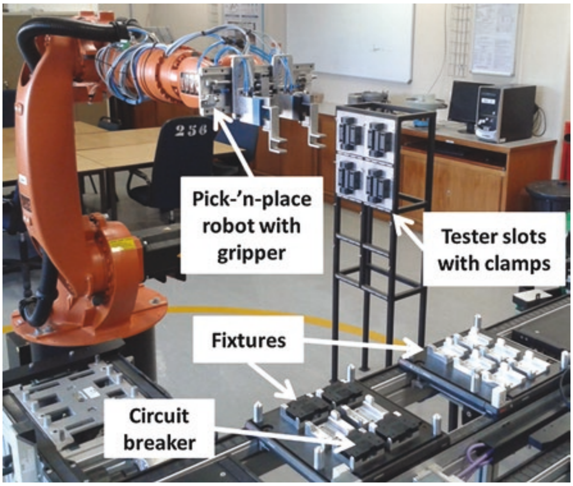

Fig. 1 Circuit breaker test station

3 Holonic Control

3.1 Holonic Architecture

There are several existing reference architectures which specify the mapping of manufacturing resources to holons and to structure the holarchy (e.g. [8, 11]). Of these reference architectures, the most prominent is that of PROSA [12].

Product-Resource-Order-Staff Architecture (PROSA) defines four holon classes: product, resource, order and staff. The first three classes of holons are basic holons, which interact by means of knowledge exchange. The process knowledge, which is exchanged between the product and resource holons, is the information describing how a certain process can be achieved through a certain resource. The production knowledge is the information concerning the production of a certain product by using certain resources—this knowledge is exchanged between the order and product holons. The order and resource holons exchange process execution knowledge, which is the information regarding the progress of executing processes on resources.

Staff holons are considered to be special holons which aid the basic holons by providing them with expert knowledge to reduce work load and decision complexity.

3.2 Resource Holon Internal Architecture

A resource holon requires several capabilities, such as communication, execution control and hardware interfacing. The resource holon model used for the implementation is described in this section.

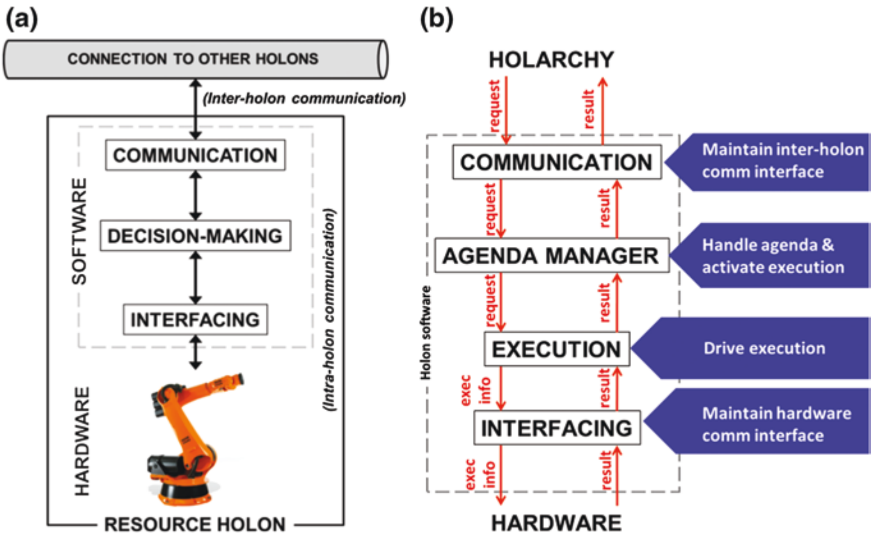

Fig. 2 **a** A generic (adapted from [14]) and **b** the adapted resource holon model

Individual holons have at least two basic parts [13]: a functional component and a communication and cooperation component. The functional component can be represented purely by a software entity or it could be a hardware interface represented by a software entity. The communication and cooperation component of a holon is implemented by software. This view of the internal architecture of a resource holon, as illustrated in Fig. 2a, is shared by Leitao and Restivo [14].

The communication component is responsible for the inter-holon interaction—i.e. the information exchange with other holons in the system. The decision-making component is responsible for the manufacturing control functions, and so regulates the behaviour and activities of the holon. The interfacing component provides mechanisms to access the manufacturing resources, monitor resource data and execute commands in the resource.

4 Erlang-Based Control Implementation

4.1 Product, Order and Staff Holon Implementation

Though not the focus of this paper, product, order and staff holons are included in the holonic control implementation. A product holon for each type of circuit breaker is included—this holon contains the information relating to testing parameters and the sequence. For each breaker on the incoming fixture an order holon is launched to drive production. These holons acquire the resource services necessary to complete the testing process. A staff holon is included to facilitate the allocation of resource services to requesting order holons.

4.2 Resource Holon Implementation

For the presented implementation a resource holon was created for the robot and each of the tester slots. While the implementation of the robot holon is complete, the service of the tester slot holons are simulated by replacing their hardware components with timer processes.

For the robot resource holon, the software components are implemented on a separate PC which interfaces with the hardware via the robot's dedicated controller. The internal holon architecture, inter- and intra-holon communication and the holon functional components are briefly discussed in this section.

Internal Architecture and Communication. For the Erlang/OTP implementation, the internal architecture of a resource holon (Fig. 2a) is adapted to that shown in Fig. 2b. Though the *Communication* and *Interfacing* components are present in both models, the *Decision-making* component in Fig. 2a is split into two components, namely the *Agenda Manager* and *Execution* components.

The communication within the Erlang implementation can be classified as either inter- or intra-holon communication. Inter-holon communication is the interchange of messages between the different holons in the system, while intra-holon communication refers to the messages sent between the holon's software and hardware components.

Messages follow the tuple format {*Sender*, *Message*}, where *Sender* holds the address of the process sending the message and *Message* holds the payload of the message. The payload, for messages received by a resource holon, is in the form of a record.

In addition to the inter-holon communication, Fig. 2b also shows intra-holon communication in terms of *requests*, *results* and *execution information*. As the *Communication* component receives messages from other holons requesting a service, *request* messages are formulated and forwarded to the *Agenda Manager* component. The *Agenda Manager* processes the request and responds to the *Communication* component, which in turn formulates and sends a reply to the requesting holon. The *Agenda Manager* can also send a message to the *Execution* component to activate execution. The *Execution* component parses the message to extract the *execution information* which is passed on to the hardware. The hardware, and subsequently the *Execution* component, gives feedback in the form of *result* messages.

Holon Functional Components. The resource holon model of Fig. 2b has four components: *Communication*, *Agenda Manager*, *Execution* and *Interfacing*.

The *Communication* component of the resource holon is responsible for maintaining the inter-holon communication interface. It receives request messages from other holons in the system, evaluates the message type and content and forwards the message to the appropriate holon component. The holon component then returns a result message, which the *Communication* component then sends to the requesting holon.

The component is implemented as a single Erlang process running a *receive-evaluate* loop. This recursive process receives messages from other holons and, by means of pattern matching, identifies relevant messages and then forwards the necessary information to the appropriate holon component. The *Communication* component's process also receives intra-holon messages—by the same means the messages are forwarded to the corresponding holon.

The *Agenda Manager* component manages the service of the resource holon. The component manages a list of service bookings by order holons and triggers the *Execution* component, with the necessary execution information, according to the agenda.

The *Agenda Manager* component is implemented through two processes—a *receive-evaluate* loop, for receiving messages, and a generic finite state machine (FSM) behaviour (using the OTP *gen_fsm* library). Through pattern-matching, received messages are related to events which cause state transitions in the FSM.

The *Execution* component of the holon drives the hardware actions which constitute the service(s) of the resource holon. It activates a sequence execution of hardware functions, with the necessary execution information.

The *Execution* component is also implemented using a *receive-evaluate* loop, for receiving messages, and a generic FSM behaviour. The required sequence of hardware actions is formulated into this FSM. With each execution state, the necessary activation and information messages are sent to the hardware via the *Interfacing* component. The process receives feedback regarding the execution status from the hardware—these messages are then used as events to trigger the transitions between the states. When execution is completed, the execution result is forwarded to the *Agenda Manager* and *Communication* components and ultimately replied to the order holon.

Figure 3a shows the execution state diagram for the pick-'n-place robot holon. This example shows three states: "ready", "picking" and "placing"—each representing an execution state of the robot. The FSM switches between states in accordance with received messages from the *Agenda Manager* and the hardware.

The *Interfacing* component maintains the communication interface between the Erlang control processes and the program on the robot controller. This component isolates the hardware-specific communication structures from the *Execution* logic.

This component is implemented using a *receive-evaluate* loop for receiving messages and a process for TCP communication. For TCP communication, the process utilizes communication functions from the OTP *gen_tcp* and XML functions from the XMErL libraries [15].

In addition to the OTP functionality used in the holon implementation described above, more tools offered by Erlang/OTP are available for enhancing the implementation. Two tools which can be very useful are the *Supervisor* and *Logging* modules. For this implementation, a *Supervisor* process for all the discussed components is included. The *Supervisor* process launches and shuts down the processes in a specified order and restarts the components if they fail. Erlang/OTP includes an *error_logger* module [16] which is used to output error,

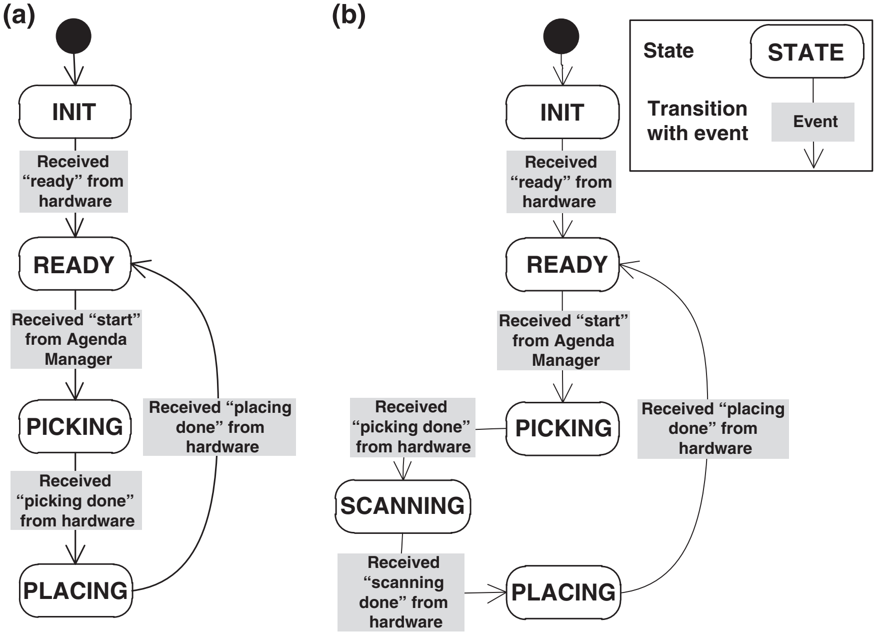

Fig. 3 *Execution* state diagrams **a** before and **b** after adding the scanning function

warning and information reports to the terminal or to file. The format of these reports can be customized according to the needs of the application.

5 Reconfiguration Experiment

A reconfiguration experiment was performed on the case study implementation to demonstrate the reconfigurability of the Erlang-based resource holon. The experiment entailed a change to the service that is provided by the robot holon—more specifically, the service was adjusted to include a scanning operation. The pick-'n-place robot must then, prior to placing, bring the circuit breaker to the vicinity of a scanner.

The added scanning function is only intended for diagnostic purposes and does not entail a change to the product information. The scanning function must be included in the *Execution* component of the robot holon. This means that an additional state must be added to the FSM. The state diagrams of the FSM before and after the addition of the scanning function are shown in Fig. 3.

The following code snippet shows the code for the FSM prior to the addition of the scanning operation:

```
1)init(_) -> {ok,ready,[]}.
2)%STATE: ready
3)ready(Msg=#service{message_type=start,info=#coords{}},_) ->
4)  robot_pi ! {robot_exec,
5)  #service{message_type=start, info=Msg#coords.pick_coords}},
6)  {next_state,picking,[Msg#service.info]}.
7)%STATE: picking
8)picking(Msg=#service{message_type=done,result=true},
9)Coords) ->
10)  robot_pi ! {robot_exec,
11)  #service{message_type=start,
   info=Coords#coords.place_coords}},
12)  {next_state,placing,[]}.
13)%STATE: placing
14)placing(Msg=#service{message_type=done,result=true}, _) ->
15)  robot_am ! {robot_exec,
   Msg#service{message_type=done,result=true}},
16)  {next_state,ready,[]}.
```

The states are defined as function heads (e.g. lines 3, 8 and 14)—the functions take two input arguments: a transition event and the state data. When the transition event occurs (e.g. a message is received), actions are performed and the new state is specified. Here the actions involve sending messages to other processes using the "`!`" operator (e.g. lines 4, 10 and 15). The new state to transition to is specified by `{next_state, StateName, StateData}`, as is shown in lines 6, 12 and 16.

The following code snippet shows the inserted code for the additional scanning operation:

```
7)%STATE: picking
8)picking(Msg=#service{message_type=done,result=true},
   Coords) ->
9)  robot_pi ! {robot_exec,
#service{message_type=start, info=?ScanCoords}},
10)  {next_state,scanning,[Coords]}.
11)%STATE: scanning
12)scanning(Msg=#service{message_type=done,result=true},
   Coords) ->
13)  robot_pi ! {robot_exec,#service{message_type=start,
   info=Coords#coords.place_coords},
14)  {next_state,placing,Coords}.
15)%STATE: placing
16)placing(Msg=#service{message_type=done,result=true}, _) -> …
```

The inserted code shows the definition of the new *scanning* state and, in lines 10 and 14, updates the transitions from and to the *picking* and *placing* states. The fixed coordinates of the scanner are defined in the module as the macro `?ScanCoords`. The code shown above is added to the *Execution* FSM module and can, through hot code-loading, replace the old FSM code while the holon is operating.

6 Conclusion

RMSs commonly employ holonic control architectures to enable the rapid reconfiguration of hardware and control resources to adjust production capacity and functionality. This paper shows that Erlang/OTP is an attractive solution for implementing holonic control and presents an implementation of a resource holon as example.

The implementation example uses a pick-‘n-place robot as resource holon. The robot picks up circuit breakers from a fixture, places them in testers and ultimately removes them again. The paper describes the implementation of the functional holon components as Erlang processes, with specific use of the OTP generic finite state machine library. The reconfigurability of the holon is demonstrated through an experiment where an additional operation is added to the pick-‘n-place process. The experiment shows that reconfiguration is easy, as the FSM code offers good encapsulation of functionality and state transitions are clearly defined and easily changed. The reconfiguration could also have been done during holon operation.

Future work will entail the expansion of the Erlang/OTP implementation to the execution control system for an entire manufacturing cell, in which all of the PROSA holons will be incorporated.

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Part II

Service-oriented Management and Control of Manufacturing Systems

ANEMONA-S + Thomas: A Framework for Developing Service-Oriented Intelligent Manufacturing Systems

Adriana Giret and Vicente Botti

Abstract New technologies are revolutionizing the way manufacturing and supply chain management are implemented. The convergence of Internet and manufacturing systems provides the basis for the creation of a new generation of computing solutions that can dramatically improve the responsiveness of organizations to better communicate with their customer and suppliers. In this work a specific framework for Service-oriented Intelligent Manufacturing System is presented. The proposed approach provides specific development steps and guidelines for implementing service-oriented manufacturing systems. Moreover, we exemplify and evaluate the usefulness of the proposed approach with a case-study description.

Keywords Service-oriented manufacturing · Multi-agent system · Holonic manufacturing system

1 Introduction

Innovation and utilization of advanced information and communication technologies are becoming more and more important to an enterprise. New technologies are revolutionizing the way manufacturing and supply chain management are implemented. The convergence of Internet and manufacturing systems provides the basis for the creation of a new generation of computing solutions that can

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A. Giret (✉) · V. Botti
Department of Computer Systems and Computation,
Polytechnic University of Valencia, Valencia, Spain
e-mail: agiret@dsic.upv.es

V. Botti
e-mail: vbotti@dsic.upv.es

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dramatically improve the responsiveness of organizations to better communicate with their customer and suppliers. Moreover, this new situation makes possible the rapid and easy on-demand creation of virtual manufacturing enterprises (open manufacturing systems) made up of different manufacturing partners that collaborate in order to fulfil the customer needs.

Collaborative manufacturing environments demonstrate considerable potential in responding to this need. A collaborative environment integrating diverse information systems can enable the creation of “virtual” enterprises with competencies to effectively and efficiently share their knowledge and collaborate with each other in order to compete in a global market. To do so, it is crucial to collaborate “electronically” via Internet Web-based technologies. In order to coordinate multiple manufacturing activities from different companies in an open manufacturing process and to guarantee the integration of different engineering tools, it is very important to have an efficient collaborative e-Manufacturing environment.

Multi-agent system (MAS) represents one of the most promising technological paradigms for the development of open, distributed, cooperative, and intelligent soft-ware systems. Moreover, the areas of Service Oriented Computing and Multi-agent Systems are getting closer and closer. Both approaches trying to deal with the same kind of environments formed by loose-coupled, flexible, persistent and distributed tasks [1]. An example of this fact is the new approach of Service Oriented Multi-agent Systems (SOMAS). In this work we present an infrastructure for developing service-oriented Intelligent Manufacturing systems. The proposed approach provides specific development steps and guidelines for implementing service-oriented manufacturing systems. Moreover, we exemplify and evaluate the usefulness of the proposed approach with a case-study description.

2 ANEMONA

ANEMONA [2] is a MAS methodology for Holonic Manufacturing System (HMS) analysis and design that is based on the Abstract Agent notion [3] and the HMS modelling requirements [4]. ANEMONA integrates features from HMS, MAS and Enterprise Modelling techniques [5, 6] to engineer Intelligent Manufacturing Systems.

ANEMONA defines the manufacturing system by dividing it into more specific characteristics that form different views. These views are defined in terms of MAS technology; therefore, we talk about agents, roles, goals, beliefs, organizations, etc. There are five views. The **Agent Model** is concerned with the functionality of each agent/holon: responsibilities and capabilities. The **Organization Model** describes how system components (agents/holons, roles, resources, and applications) are grouped together. The **Interaction Model** addresses the exchange of information or requests between agents/holons. The **Environment Model** defines the non-autonomous entities with which the agent/holon interacts. The **Task/Goal Model** describes relationships among goals and tasks, goal structures, and task structures.

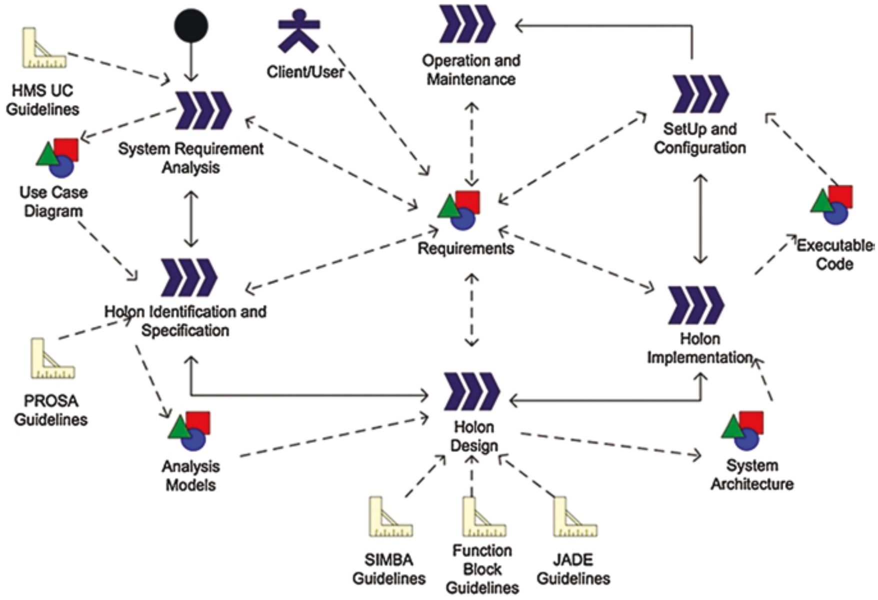

Fig. 1 Stages of the methodology

In Fig. 1 one can see the development stages of ANEMONA.[1] The first stage, **System Requirement Analysis** and the second stage, **Holon Identification and Specification** define the analysis phase of our approach. The aim of the analysis phase is to provide high-level HMS specifications from the problem **Requirements**, which are specified with the help of the problem domain experts and which can be updated by any development stage. The analysis adopts a top-down recursive approach. One advantage of a recursive analysis is that its results, i.e. the **Analysis Models**, provide a set of elementary elements and assembling rules. ANEMONA provides specific guidelines [2] to help the engineer during the analysis phase. The **HMS UC Guidelines** can be used to identify and specify Use Cases, while the **PROSA Guidelines** are used to identify and specify PROSA types of agents [8]. The next stage in the development process is the **Holon Design** stage that is a bottom-up process to produce the **System Architecture** from the **Analysis Models** of the previous stage. In this phase, the engineer can use three guidelines [2], depending on the type of the MAS system to control the factory. The **SIMBA Guidelines** are for the SIMBA MAS implementation platform [9]. The **JADE Guidelines** are for the JADE agent platform [10], and the **Function Block Guidelines** are for implementing the physical processing part [11] of the factory resource agents. The aim of the

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[1] The specification of the development process of ANEMONA is presented using SPEM diagrams [7].

Holon Implementation stage is to produce an **Executable Code** for the **SetUp** and **Configuration** stage. Finally maintenances functions are executed in the **Operation and Maintenance** stage.

3 Thomas

The aim of the THOMAS project (http://www.gti-ia.upv.es/sma/tools/Thomas/) is to advance and contribute solutions in the development of a MAS architecture suitable for the generation of virtual organizations in open environments, as well as a support platform which allows these systems to be implemented. More specifically, the aim is to develop mechanisms based on organizational structures and virtual organizations that optimize and regulate the coordination of services in open multi-agent systems.

THOMAS [12] is an open-agent platform that employs a service-based approach as the basic building blocks for creating a suitable platform for intelligent agents grouped in virtual organizations. It feeds on the FIPA (http://www.fipa.org) architecture, but extends its main components the Agent Management System (AMS) and the Directory Facilitator (DF) into an Organization Management System and a Service Facilitator, respectively.

Therefore, the two main components of the THOMAS approach are as follows:

- Service Facilitator (SF), which is a service manager that registers services provided by external entities and facilitates service discovery for potential clients.
- Organization Management System (OMS), which is responsible for the management of virtual organizations, taking control of their underlying structure, the roles played by the agents inside the organization and the norms that rule the system behaviour. More specifically, the OMS component is in charge of controlling how organizational units are created; which entities are participating inside; how these entities are related to each other and which roles they play through time.

4 The ANEMONA-S + THOMAS Framework

In this work we propose ANEMONA-S, which is an extension of ANEMONA in order to include specific service-oriented guidelines to help the system engineer when developing service-oriented Intelligent Manufacturing Systems. We connect ANEMONA-S with THOMAS in order to provide a complete development frame-work for systems of this kind.

In our approach we focus on Service-Oriented MAS [1] view of collaboration that is compatible with Web service standards [13] based on XML, SOAP, and WSDL. We define a Web-based MAS collaboration system for e-Manufacturing which could be used to support small to large-scale businesses that wish to collaborate in an open virtual enterprise through services available on their respective online manufacturing systems.

Figure 2 shows the analysis activities where the new **Service Guidelines** complete the methodology in order to make it specific for service-oriented manufacturing environments. Whereas, Table 1 overviews these guidelines. The extended activities are marked with a wider line in Fig. 2.

In the activity **Identify the Tasks and Services which implement the Use Cases**, the system engineer can use the Service Guidelines 1 and 2 in order to figure out which system functionalities will be services provided by the system under design. Whereas guidelines 3–5 help the system developer to identify the internal services provided and required by internal system elements. In order to complete the holon specification guidelines 6–8 can be used. These guidelines help the designer when specifying the holon behaviour and implementation.

The process development when using the framework is the following:

- From the system requirement identify the system goals and use cases. Please refer to the ANEMONA **Use-Case guidelines** [2].
- From the Use-Cases derive the services provided and required by the system. Use guidelines 1–3 from Table 1.
- From the Use-Cases derive the services provided and required by the system. Use guidelines 1–3 from Table 1.
- Complete the services' specifications using Table 1 and the service template defined in [12].

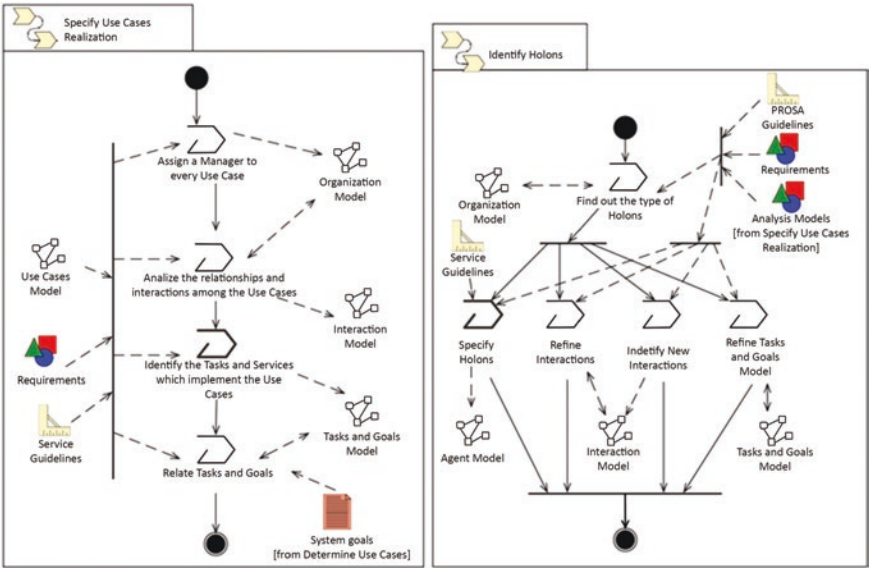

Fig. 2 ANEMONA-S analysis activities

Table 1 ANEMONA-S service guidelines

ID	Guideline
1.	Associate a new service description to each system functionality that is provided to external users of the system
2.	If the system requires a functionality from outside the system, identify a service request with it
3.	If two use cases requires interactions identify a new service to implement this interaction
4.	For every service (from guidelines 1–3) complete a **Service Specification Template** defined in [12]
5.	For every service (from guidelines 1–3) make sure that there is one or more holons responsible for providing it
6.	Complete the holon specification from the service profile specified in the **Service Specification Template**
7.	Complete the **Interaction Model** by means of sequences of services executions. Make sure that every service in an interaction model has its corresponding **Service Specification Template**
8.	Translate the **Service Specification Template** into THOMAS code using the programmer's guidelines (http://www.gti-ia.upv.es/sma/tools/magentix2/index.php)

- Complete the Holon identification and specification following the specification and modelling process defined in [2].
- Complete the interaction modelling with the help of guideline 7 of Table 1 and the detailed interaction modelling defined in [2].
- Build the System architecture including the implementation details of the target execution platform. For a complete description of this step, see [2] and [12]. At the same time, use guideline 8 of Table 1 for the services implementation in THOMAS.
- Perform the validation and verification steps defined in [2] and execute the benchmarks defined in (http://www.gti-ia.upv.es/sma/tools/magentix2/index.php) in order to measure performance and identify possible errors.
- Install and configure the system at the execution platform.
- Perform maintenance activities see last development process described in [2].

5 Case-Study: An e-Manufacturing Environment

In order to exemplify how would be the diagrams derived from the proposed frame-work, we present in this section a brief description of a case study about an Agent Supported e-Manufacturing environment (ASeM). It is built as a Web-based application in which different companies can join temporarily alliances in order to take part into virtual enterprises. An open virtual enterprise can be viewed as a temporary alliance between various partners and services to support certain activity or a set of activities [14]. In ASeM we look into open agent-based technology to support Web-based collaboration within open virtual enterprises.

In order to evaluate the proposed framework we have executed an experiment in which two different engineering teams, with the same expertise on agent-based technology, developed the system with two different approaches: ANEMONA, and ANEMONA-S + THOMAS. The goal of the evaluation was to figure out the easy to use and the usefulness of the Service Guidelines when developing the system. The first team derived a system where there is no service identification. A set of holons implements the functionality of the system executing cooperation scenarios by means of message passing (FIPA ACL). Whereas, the second team derived a system implemented by a service-oriented multi-agent system following the Web service standards [13] based on XML, SOAP, and WSDL. Which system is better? In terms of functionality and number of holons, the second team derived a system with fewer holons that compiles similar services into fewer providers. In terms of development time, the first team finished first the system. This could be because no team was expert on SOA implementation and there was required two weeks of training in the second team in order to get the services running in the platform. Nevertheless, the interaction with the second system was much easier and very "smooth" to add and delete new virtual enterprises during run-time by the users. In the following paragraph a description of the key elements of the second system and their executions for creating a new virtual enterprise is described.

When a manufacturing company registers to use ASeM the user fills in a series of Web-based forms to enter data, which is stored in the customer description associated with its **Customer Mediator** agent. At the same time collaboration related data is maintained by the **Customer Mediator** such as the set of services the customer wish to offer and the various partners it has made virtual enterprise agreement with. A company registered in ASeM has many options to execute. It may configure its agents in order to define or update their services. It may order its **Customer Mediator** agent to search for interesting virtual enterprise ventures to joint to. It may get information on the status of the different collaboration scenarios in which it is a partner. It may query the different agreements it has made using ASeM. It can get the different work-orders it has to execute in its factory floor. Finally, it can decide to exit a given virtual enterprise.

Figure 3 depicts the cooperation diagram for an interactive virtual enterprise creation. A registered manufacturing company starts the cooperation scenario defining the virtual enterprise features interacting with its **Customer Mediator** agent (using the Web-based interface). In this definition process, the virtual enterprise purpose is stated and the required **Work Order Agents** are defined.

This data is used by the **Customer Mediator** agent in order to request the creation of the virtual enterprise to the **OVE System Manager**. When receiving such a request the **OVE System Manager** queries the **Trust and Security Mediator** in order to get trust data associated with the customer for the type of virtual enterprise that is being requested. Depending on the trust data, the **OVE System Manager** decides to create or not the virtual enterprise. In the first case the virtual enterprise is accepted and registered in the system, together with the list of **Work Order Agents** associated. In this process the **OVE Service Manager**

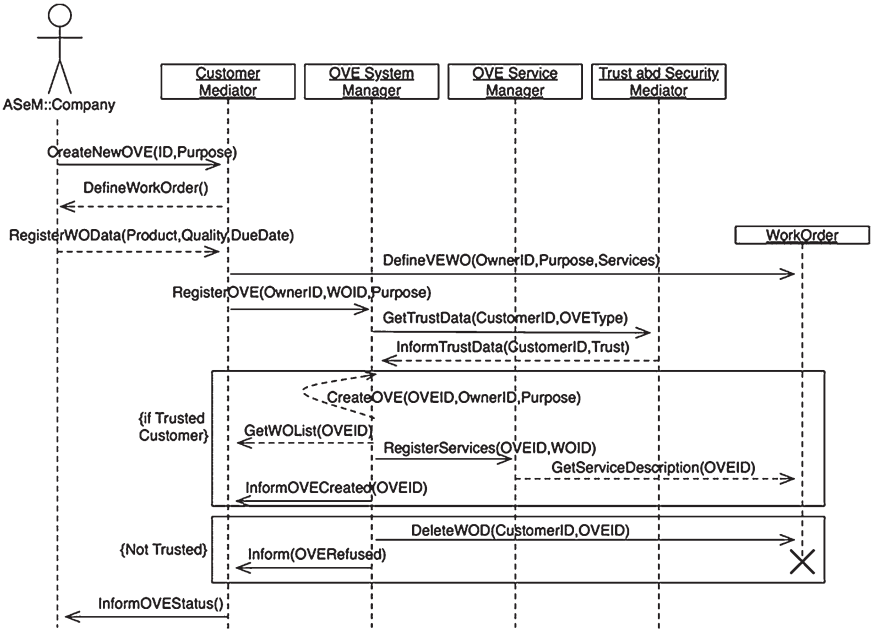

Fig. 3 Cooperation diagram for the creation of an open virtual enterprise

also registers the services defined for the virtual enterprise. Finally the customer is informed on the creation of the virtual enterprise. When the virtual enterprise is refused, due to trust data, the **Work Order Agents** are deleted from the system and the customer is informed as well.

A manufacturing company can order its **Customer Mediator** agent to search for possibilities to join a virtual enterprise. In this case the **Customer Mediator** agent starts a cooperation scenario with the **Collaboration Mediator** agent in order to keep updated information on the virtual enterprises that are advertising collaboration opportunities. When a collaboration opportunity is found the **Collaboration Mediator** facilitates all the data to the **Customer Mediator** who estimates the advantages to collaborate in. In case the **Customer Mediator** decides to collaborate, the **Collaboration Mediator** puts in contact the **Customer Mediator** with the **Production Mediator** agent and the **Customer Mediator** of the given virtual enterprise. All this process is supervised by the **Trust and Security Mediator** agent.

6 Conclusions

In this work we have proposed a specific framework for developing Service-Oriented Manufacturing Systems. The proposed framework is made up of a new methodology called ANEMONA-S, which is an extension of the ANEMONA method.

The design models derived from ANEMONA-S are translated into execution code and can be executed on the THOMAS platform, which is a service-oriented agent platform. We have also validated the proposed approach by means of an experiment in which a Web-based application for virtual enterprise definition and execution is implemented. The results of the experiment show that the derived system using ANEMONA-S + THOMAS is correct and complete.

We are working right now on tuning and completing some modules of THOMAS in order to have automatic code generation for some typical cooperation scenarios in any intelligent manufacturing systems. Those scenarios are: team formation, team deletion, team monitoring, etc.

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An Orchestration Engine for Services-Oriented Field Level Automation Software

Christoph Legat and Birgit Vogel-Heuser

Abstract The flexibility of field level automation software is inevitable in order to realize intelligent, flexible production control systems. One way to achieve increased flexibility of field level automation software is to separate the control flow of software, i.e. the workflow, from executing respective functionality as typically applied in business software. This paradigm is used also within service-oriented applications where workflow models define the orchestration of services. In order to apply this paradigm to field level automation software, some conditions have to be considered. Especially, field level automation software is typically operated on programmable logic controllers according to the cyclic executed IEC 61131-3 standard. In this paper, a service model is presented which is applicable to such field level automation software and the behaviour of an orchestration engine which can operate in IEC 61131-3 environments is specified. Its applicability on a lab-scaled manufacturing system is presented.

Keywords Flexible field level control · Service-oriented architecture · Orchestration engine · Workflow patterns · Manufacturing system

1 Introduction

To react on different changing conditions influencing production operations, various approaches on intelligent manufacturing have been conducted [1]. In manufacturing automation, the space of actions in which the behaviour of a machine or plant can be automatically adjusted is limited basically by the capabilities of the hardware and the functionality implemented within field level automation software.

C. Legat (✉) · B. Vogel-Heuser
Institute of Automation and Information Systems, Technische Universität München,
Munich, Germany
e-mail: legat@ais.mw.tum.de

B. Vogel-Heuser
e-mail: vogel-heuser@ais.mw.tum.de

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For implementing field level automation software, the signal-oriented languages as defined in the IEC 61131-3 standard [2] are used which are executed cyclically on programmable logic controllers (PLCs). In practice, these languages are applied to implement what a plant should do, i.e. the technical process to manufacture a good. This is one of the possible control processes which can be realized within the plant. In contrast, modeling what a plant is able to do would improve flexibility because the overall space of action is implemented [3]. These overall capabilities of a plant can be described by a model of fine-grained control functionalities together with a description of the way they can be composed [4]. The way how these given control functionalities are orchestrated can be adjusted within given boundaries to flexibly adjust behaviour of IEC 61131-3 based field control software [5].

In computer science, especially in enterprise and business IT, this approach is recent practice: workflow models are used which define an orchestrated pattern of an activity. An orchestration engine (OE) realizes the control flow automatically by interpreting a workflow model. The service-oriented architecture follows this paradigm and comes along with necessary standards and technologies to realize this vision.

Research conducted on service-oriented manufacturing already investigated the applicability of this paradigm [6–9] and proposed various applications and necessary adaptations to apply service-orientation to manufacturing engineering and control [10–13]. Most of them act analogously to business IT in a strict event-based manner postulating a paradigm shift for field level automation software. A combination of both worlds, the predominant IEC 61131-3 standard with the service-oriented paradigm did not exist until now. Therefore, an orchestration engine which can be operated within IEC 61131-3 environments is presented in this paper. In the next section, a brief discussion of necessary design aspects of services for field level automation software and a corresponding service and workflow model is presented. In Sect. 3, the orchestration engine's behaviour is specified in detail. Subsequently, the application of workflow modeling and orchestration engine for a lab-scaled manufacturing system and implementation details of the orchestration engine executable on standard industrial hardware is described in Sect. 4. The paper is concluded in Sect. 5.

2 Field Level Service Model and Workflow Model

The service oriented architecture is "a paradigm for exchange of value between independently acting participants" [14]. In the remainder of this paper, we focus on two specific logical participants: the orchestration engine (OE) and field level services both executed on PLCs. Here, we consider at first both executed on a single PLC but the concept can be extended to distributed, networked automation systems when considering further aspects like time delays or jitter introduced by the network. Field level services encapsulate functionalities providing either plain software capabilities or functionality for manipulating the state of the physical environment or control system. In (computer science) literature, various definitions about mandatory or optional design principles of services exist [15–17], e.g. statelessness, reusability, and composability. In the following, a selected set of design principles is discussed which is relevant to the execution specification of an OE and the definition of field level services. Subsequently, a basic workflow model is introduced and coupled to an abstract field level service model.

2.1 Field-Level Service Characteristics

A frequently discussed design principle of services is its *statelessness*. A stateful service is one where subsequent requests to the service depend on the results of the first request. In contrast, a stateless service is one that provides a response after the request, and then requires no further attention. In general, statelessness is preferable because no complex interaction has to be considered. In cyclic IEC 61131-3 execution environments, software code of a service is only executed if it is called in each cycle. Furthermore, the execution of the service code has to terminate within a cycle. For example a service which implements an open loop controller for extracting a pneumatic cylinder: after opening the respective pneumatic valve, the cylinder extracts. The extraction of the cylinder takes (depending on the size of the cylinder and the pressure) for example some seconds whereas the PLC is operated with a cycle time of some milliseconds. The service is finished when a binary sensor indicates the complete extraction of the cylinder. Consequently, the service has to be called in various execution cycles of the PLC and its behaviour depends on previous service calls. Therefore, field level services executable in IEC 61131-3 environments have to be mostly *stateful*.

Service-orientation is a design paradigm carrying out a separation of concerns. Services encapsulate well-defined functionality which can be repurposed to solve recurring required functionality. Accordingly, *reusability* is a major design principle for services. In context of field level services, reusability targets to reuse especially control functionality of specific manufacturing facilities, e.g. the extraction or retraction of a specific pneumatic cylinder. Typically, as more fine grained services are defined, the more reusable they are. *Composability* of services is a major concern when focusing on reusability. It enables to compose services to realize coarse-grained functionality, e.g. sorting based on various pneumatic cylinders for ejecting material transported on a conveyor. To define a composite service, a workflow model is used.

A further design principle of field level services without any respective design principle of business services is the *independency* of concurrent executed services. Two concurrently executed services are dependent if both use the same actuator resource contradicting, i.e. each service sets contradictory actuator control values. Otherwise it is independent. For field level control services, independency is important.

2.2 Workflow and Service Model

Workflow models are necessary to describe compositional aspects of services which are essential in the automation domain [18]. A workflow is built upon different workflow patterns [19]. They are used to model dependencies with respect to their execution order. In addition, some annotations like temporal aspects are possible. Furthermore, process descriptions are required to overcome varying granularity of services by aggregation (composition). A specific workflow defines the behaviour which should be realized by an OE. For sake of simplicity and clarity, solely a selected set of basic workflow patterns is introduced here: sequence, parallel split and synchronization pattern. For a detailed discussion of various further workflow patterns, see [19, 20]. As exemplary workflow notation, UML activity diagrams (AD) are used for exemplifying the workflow patterns [21].

The *Sequence Pattern* defines sequential orders of activities. An activity in a sequence is enabled after the completion of the preceding activity. In AD, a sequence is indicated by an arcs between activities. The *Parallel Split* is the basic pattern which represents the divergence of a branch into two or more parallel branches each executed concurrently. After completing an activity with successive parallel split, two or more parallel activities are started and executed independently of each other. Within ADs, the element "fork" is used for explicit visualization of parallel splits, but in some other notations also implicitly definitions (e.g. by multiple outgoing arcs of an activity) exist. Subsequently to a split, an OE has to execute various branches concurrently. The *Synchronization Pattern* defines the convergence of two or more branches into a single subsequently executed branch. Analogously to the parallel split, synchronization might be defined implicitly (e.g. by multiple incoming arcs to one activity) or explicitly as e.g. by modeling element "join" of ADs. A single subsequent branch is executed, after completion of all previously concurrent branches, i.e. an OE remains in the "join" element, until all respective concurrent branches have finished.

Figure 1 depicts the summary of discussed design principles in Sect. 2.1 within an abstract field level service model. A service can either be an atomic service or a composite service. The characteristics of an exemplary workflow model

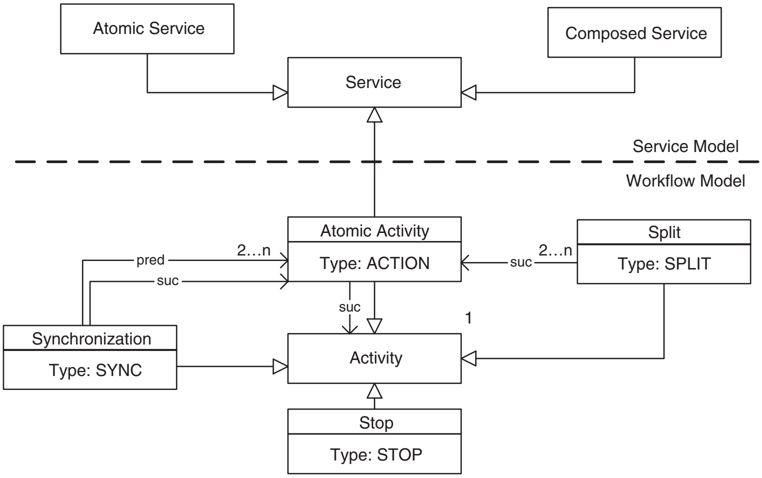


Fig. 1 Abstract field level service model (*top*) and exemplary workflow model (*bottom*)

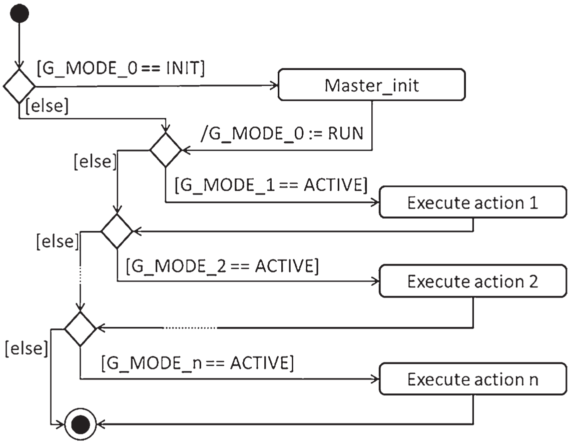
for composed services as discussed above are summarized visually in Fig. 1. If an activity inside a composition model is executable (is of type action and not a workflow element), it is a service according to the service model. A sequence is realized as a kind of a linked list by a successor relation (suc). Workflow-specific activities are modelled as respective elements (split, sync and stop).

3 Orchestration Engine for Field Level Services

For realizing an OE which can execute workflows according to a given workflow model and operates within cyclic IEC 61131-3 environments, a detailed specification of its behaviour is required. For visualizing behaviour of OEs, UML state diagrams (SD) are used with the assumption that SDs are executed within one PLC cycle. The OE's main routine which provides basic management and scheduling functionality is called each execution cycle of a PLC (cp. Fig. 2). To enable the OE to remember about his recent activities among cycles, some cycle-persistent variables are used. According to the IEC 61131-3 standard, no dynamic allocation of memory or function calls is available. Therefore, a fixed maximum number of concurrent branches of the workflow exists. When the OE is started, a master initialization is executed which interprets the first activity (successive to the start node) of a workflow model. Due to space limitations, the behavioural specification of the Master_init routine is not given visually. Depending on the number of concurrent branches within the workflow model, respective variables (G_MODE_i) are set to ACTIVE and the respective actions are executed accordingly. Each of these actions is a self-managing (sub-) orchestration engine (SOE) which is capable to execute workflow patterns.

For each SOE, a separate set of cycle-persistent variables are defined: MODE_i defines the recent mode of this SOE; the variable action_i defines the recent action to be executed according to the workflow model.

Fig. 2 Behaviour model of the orchestration engine's main routine as UML state diagram



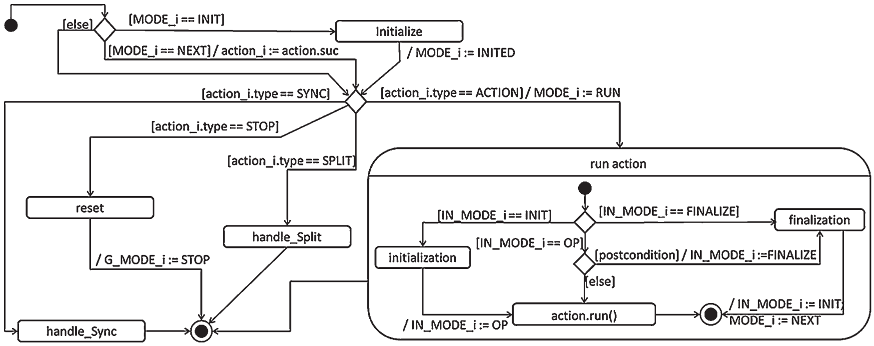


Fig. 3 Behaviour model of sub-orchestration engine's routine as UML state diagram

When executing a respective SOE the first time (indicated by mode INIT), an initialization routine is executed. Subsequently, depending on the given type of action in the workflow (indicated by action_i.type), respective routines are executed (cp. Fig. 3). For managing service execution, an additional cycle-persistent variable IN_MODE defining the internal state is used. As depicted in Fig. 3 and given by the execution semantics, the service is called each cycle (state "run action"). Depending on the IN_MODE, service initialization, finalization or the basic behaviour is executed. The action is called until a post condition indicates a successful service execution. Accordingly, these services are stateful. For handling workflow patterns, respective states for SPLIT, SYNC and STOP are defined.

4 Application to Manufacturing System Control: A Case Study

For practical evaluation of the proposed approach, a lab-scaled manufacturing demonstrator build upon state of the art industrial automation hardware is used.

As depicted in Fig. 4, the Pick and Place Unit (PPU) [22, 23] consists of four components: a stack for storing work pieces (WPs), a stamp, a sorter and a crane for picking and placing between stations. WPs are separated in the *stack* by *extracting* a vertically mounted pneumatic cylinder and pushed towards a handover position. When a WP is separated at the stack, the *crane* is *lowered* by a vertical mounted, pneumatic cylinder to subsequently *intake* the WP by its vacuum gripper. When the handover of the material was successful, the cylinder of the *stack* is *retracted* to release the WP and enable that the *crane* can *transport* the material to the stamp. In Fig. 4, transportation is given as composite service *transportStackToStamp* which consists of a sequence of *lifting*, *turning left 180°* and *lowering* of the crane. To ensure restrictions on WP handover between crane

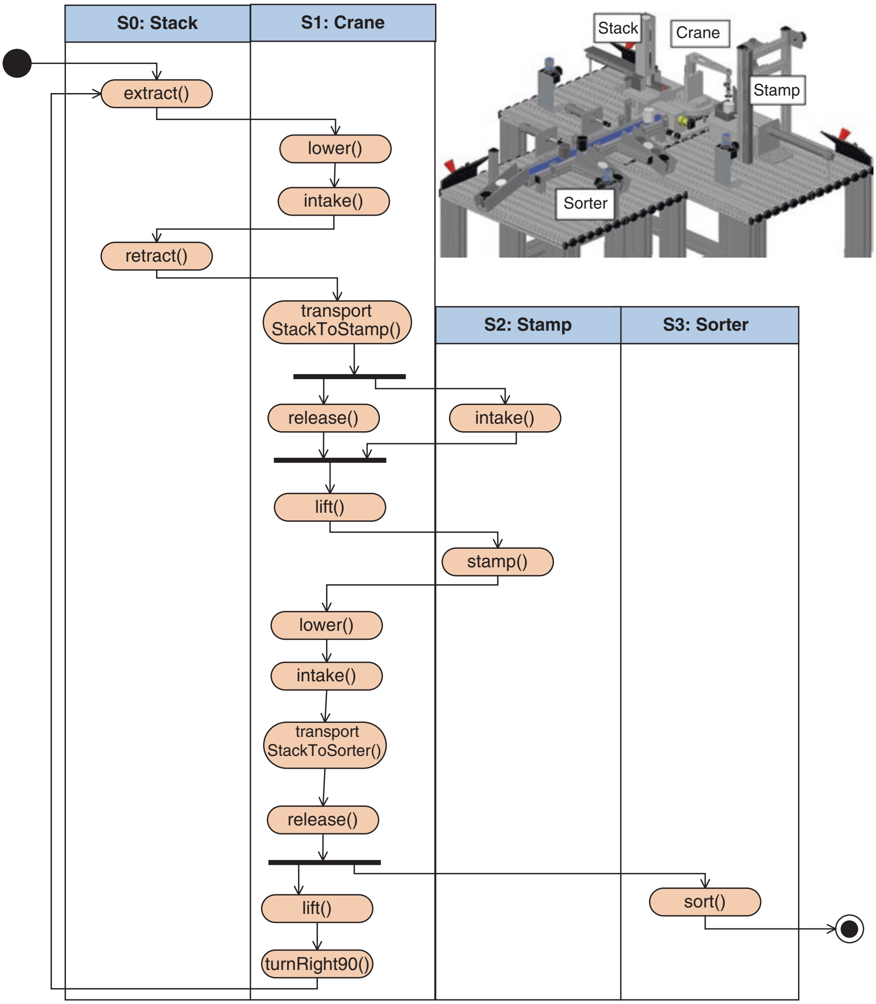


Fig. 4 Sample workflow specification of the PPU visualized as UML activity diagram (*left*) and the mechanical layout of the pick and place unit (*top right*)

and stack caused by the mechanical design, a *release* of WPs by the *crane* is only allowed if the *stack* is able to *intake* the WP concurrently. Here, a parallel split and synchronization within the workflow model is applied (cp. Fig. 4). After a successful handover of the WP from the crane to the stack, the *crane* has to be *lifted* due to mechanical restrictions before a WP can be handled by the stamp. The *stamp*'s *stamping* operation is also a composed service not detailed here (cp. [22] for details). After stamping, the *crane lowers* and *intakes* the WP. Subsequently, the composite service *transportStackToSorter* can be executed (which consists of a sequence of *lifting*, *turn right 90°*, and *lowering*) to finally *release* the WP at the sorter. Now, the WP is *sorted* (again a composite service) at the *sorter*, i.e. the WP is transported to one of the installed ramps depending on the number of WPs already in the ramps. Concurrently to the sorting (defined in the workflow model by a parallel split), the *crane turns right 90°* and starts handling the next WP by *extracting* the *stack*'s cylinder. As described, services are composed and reused frequently. For example lifting the crane is used both, in the main workflow as well as in composed services.

The OE was implemented according to the IEC 61131-3 standard within the industrial development environment CODESYS[1]. The PPU is controlled by an industrial soft-PLC (CODESYS Control Win V3) which executes OE and services. Each service was implemented manually as Function Block in Structured Text language (a programming language defined within the IEC 61131-3) according to the service model described in Sect. 2. For storing the workflow model within IEC 61131-3, various integer arrays are used. Each service has an associated unique identifier which is used to refer to the respective service to be executed. Also each workflow activity has a specific integer identifier. Since dynamic allocation of calls is not possible in IEC 61131-3, some software code of the OE depends on the set of implemented services. Therefore, interpreting service and workflow activity identifier has to be static software code whereas the workflow itself can be flexibly defined based on the values given in the arrays.

5 Summary and Outlook

Throughout this paper, an approach to decouple workflow specification and service implementation for state of the art industrial PLCs according to the IEC 61131-3 standard was presented. Required service design principles specific for implementing services on respective PLCs were discussed. An orchestration engine whose behaviour is adapted to be executable within the cyclic execution environments and capable to execute field level services was described. The applicability of the proposed concept was shown by an exemplary lab-scaled demonstrator implementation. Currently, a specific development tool to facilitate the implementation of field level services is developed. It will enable automatic generation of the orchestration engine's software code which depends on the implemented services. Furthermore, modelling workflows in UML is investigated for automatically configuring the orchestration engine. Accordingly, a model-driven approach for automatically generating the orchestration engines' IEC 61131-3 codes based on specialized UML models will be investigated.

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[1] http://www.codesys.com

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Process Specification Framework in a Service Oriented Holonic Manufacturing Systems

Francisco Gamboa Quintanilla, Olivier Cardin, Anne L'Anton and Pierre Castagna

Abstract Holonic and service-oriented architectures have been proposed as solutions for the conception of flexible and reactive systems. Flexibility being one of their main objectives depends greatly on the way information is presented to the system which can limit the flexibility of strategies at higher levels, as in process planning and reconfiguration. Although many works propose the use of services, none have been found describing what services stands for in a manufacturing context to form manufacturing processes. This paper proposes a methodology for designing manufacturing-process specifications based on manufacturing-services suitable for product driven applications that welcomes product customization. Conceptual models for processes and services are proposed in this work designed to preserve the fractal characteristics and facilitate service reutilization. Such models form part of the specification framework that will serve as a reference for the design and conception of manufacturing processes and services in Service-oriented Holonic Manufacturing Systems.

Keywords Holonic manufacturing · SoA · Product specification · Manufacturing-services · Process families

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F. Gamboa Quintanilla · O. Cardin (✉) · A. L'Anton · P. Castagna
LUNAM Université, IUT de Nantes – Université de Nantes, IRCCyN UMR CNRS 6597
(Institut de Recherche en Communications et Cybernétique de Nantes),
2 Avenue du Prof. Jean Rouxel, 44475 Carquefou, France
e-mail: olivier.cardin@univ-nantes.fr

F. Gamboa Quintanilla
e-mail: francisco.gamboa@univ-nantes.fr

A. L'Anton
e-mail: anne.lanton@univ-nantes.fr

P. Castagna
e-mail: pierre.castagna@univ-nantes.fr

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1 Introduction

An evolution in the goods market (namely: highly customized products and shorter product lifecycles) has forced companies to adopt an exhaustive search for achieving responsiveness, flexibility, a reduction of costs and an increased productivity in order to stay competitive in such new changing environment. The conception of these so called Next Generation Manufacturing Execution Systems has been challenging the community of Intelligent Manufacturing Systems for two decades now to incorporate such attributes. Holonic Architectures and Service-Oriented Architectures (SoA) have been two of the most studied and referenced solutions to this problem, in manufacturing and informatics respectively. Both of these solutions provide the necessary guidelines to create open, flexible and agile control environments for the next generation manufacturing systems. The combination of both of these principles appears to be a very attractive option as seen in works relating these two paradigms, [1–3]. However, there are no works been found, describing how a process is composed based on services, nor has been the composition of a service representing integrally a manufacturing process with an eye on its application on HMS. Moreover, flexibility, being the main attribute soled by these paradigms depends on the intrinsic flexibility found at all levels of the system. The way information is presented in the system will greatly define the flexibility limits at higher levels for finding new solutions, as in process planning and reconfiguration. For instance, if the information describing the system's components and activities fails to express the underlying capacities and possibilities, the intrinsic flexibility present in the production floor will not be identified nor control strategies will be exploited at their best. The objective of this paper is to propose a methodology for designing manufacturing process specifications based on manufacturing services that welcomes product customization and is suitable for their application on distributed and product-driven systems. Conceptual models for manufacturing process and manufacturing services are proposed in this work designed to preserve the fractal characteristics of products and promote the reutilization of operations. Fractality of services (i.e. a same model of services from the highest to the lowest levels) is especially efficient as it naturally fits to the nature of processes. Products, resulting from the execution of services, therefore need to be fractally modelled in order to take advantage of the structure of the corresponding services.

Section 2 describes briefly some approaches of process specification of works related to HMS and SoA and make as small review on existing works on process specification which inspired the propositions of this paper. Section 3 proposes a manufacturing service model, a process model for each of the process types identified and finally a specification framework based on such models.

2 Existing Process Specification in Distributed Systems

Traditionally, in manufacturing systems, process models are usually represented by linear sequences where the order of the conforming tasks is fixed a priori by process engineers based on their insight about the process nature and the production system. Such is the case in flexible job-shops [4] where the main problem is to find a solution for scheduling resource allocation for a given collection of sequences called jobs. Recent works on HMS propose to enrich the process model by considering the existence of different alternative operations for a given production state such as in [5, 6], where the authors propose Petri-net controllers for modelling alternative operations. In the same matter, [7, 8] suggest the creation of a *Logical Operating Sequence* independent from the production floor. However, none of these works elaborate on how to create such models or on a way to describe the process structure. Regarding SOA, many works suggest the integration of Web Service technology in Industrial Systems such as [9] pointing out the issues for its application, [5, 6] proposing Petri-net controllers for processes formed by services, [10] proposing a service-oriented manufacturing architecture with Multi-Agent technology, among others. Nevertheless, there have not been found works, apart those on Semantic Web-Services [1, 11, 12], with a detailed description of what a service represents in the manufacturing context and what are its composing elements in order to build fractal processes and ensure their integral description. In terms of process specification, there has been a great deal of effort devoted to the formal and philosophical specification of processes as well for the development of process models. Among these efforts there are: the Process Specification Language (PSL) [13] which is a proposition of a formal ontology providing a formal description of the components and relations that form a process; the IDEF3 [14], a process specification capturing method with a graphical language conceived to describe and represent the structural nature of a process; the Web services Description Language (WSDL) [15] dedicated to the abstract description of a service interface for its proper invocation, and the Business Process Execution Language (WS-BPEL) [16] used to describe the different workflows that can be composed by the collection of Web services found in a process. The issue is that most of these languages and methods are not intended nor suitable for describing processes in industrial applications (they are intended for enterprise-level systems) specially those involving intelligent products, or active as proposed in the analysis framework of [17] where decision making is embedded.

3 Customizable Service-Oriented Process Specification

In product customization, companies tend to adopt the development of *Product Families* [18] which recognizes the existence of scalable and modular product customization platforms. According to [19, 20], commonality found in a product family structure usually translates into a commonality in the process domain. Such idea brings rise to the concept of *Process Families* which, in the same way as product families, possess the attributes of commonality, modularity, reutilization and scalability but in the process domain [18]. A Process Family can then be seen as a collection of manufacturing operations that respond to the realization of the corresponding structural modules of a Product Family. These, now called manufacturing services, possess a proper identification and description independent from the service provider i.e. they are identified according to the added transformations, with no regard on the methods that are used for their implementation. Thanks to this, manufacturing services can be standardized and be readily available to integrate different production processes thus bringing the benefit of reusability that will reduce reprogramming efforts. Moreover, customization can be incorporated into the process at a scalable level through the parameterization of services and at a modular level through the choice of services to be involved in the process.

3.1 Manufacturing Services and Model

At a workshop level two main classes of services are: Manufacturing Services and Supply Services. A *Manufacturing Service* (M-service) performs manufacturing transformations to the main product adding value to it. A *Supply Service* (S-service) refers to the service of providing a product or sub-product to a client namely a costumer or a resource. The conceptual model for both, M-services and S-services is illustrated in Fig. 1.

A M-service is composed of one or more *Process Methods* and by a collection of *Process Parameters*. A *Process Method* represents an action or a structure of actions that transform the product and/or the world as described by the service class. Three types of process models where identified: *Product-Process Model*, *Device-Process Model* and a simple *logic address*. The first two model *Composite Services* which provide processes composed of other more granular services, while the last represents a program in the provider's controller executing an *Atomic service*. Each method implementing the service has its own set of *Attributes* used to evaluate its eligibility over other methods. A *Process Parameter* embodies a piece of information needed by the process method in order to determine the limits of the process, namely a *variable*, *port id* (for service delivery), a *material* or *sub-part*. Its cardinality reflects the flexibility of the service to reproduce a different result that adapt to different needs.

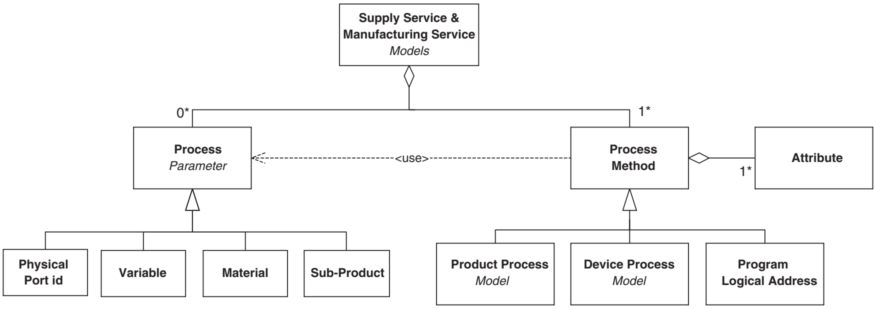

Fig. 1 Manufacturing (and supply) service model

The two main virtues of this model are: it keeps the fractal character of products and processes and welcomes the integration of scalable customization. Fractality at the product level is kept by the process parameters class which can specify the integration of a material or sub-product. Fractality is also kept at a process level through composite services whose models will be described in the next section. As seen in Fig. 1, a service can have more than one process method associated; this is due to the fact that methods are proprietary to provider and not to the service itself.

This allows the integration of different technologies that will increase the system's flexibility for re-configuration and expansion makes process specification platform independent. Reusability of services is leveraged by the decoupling of parameters from methods which through parameterization allow them to fit in different processes, thus integrating customization at a scalable level into the process domain.

3.2 *Product's Process Model*

Manufacturing processes are characterized by different aspects such as their granularity, taxonomy's category and in the concurrency of their composing services. As shown in Fig. 2, the granularity of a manufacturing process can be either composite or atomic. Composite processes can be of two types: Product Processes and Devices processes characterized by the composing services concurrency. *Product Processes* are those composed of only non-concurrent services i.e. there can only be one service executed at the time. *Device Processes,* on the other hand, are those having concurrent services i.e. more than one service can happen simultaneously and require synchronization for their execution. Fractality is also highlighted in this diagram (Fig. 2), by indicating that the composing Product-level and Device-level services

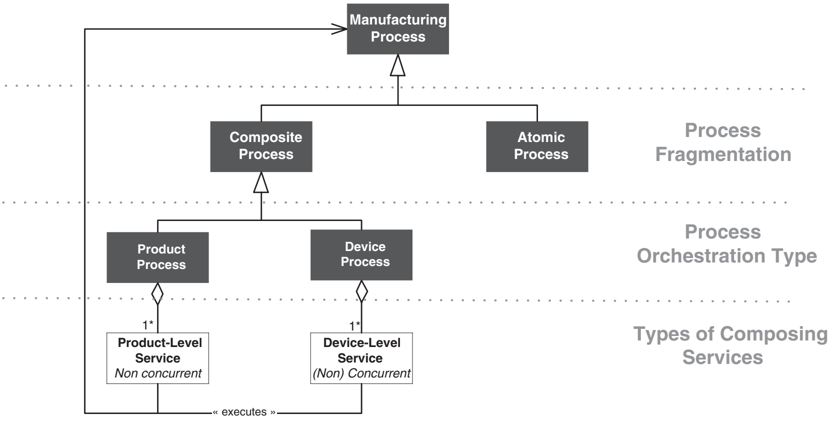

Fig. 2 Processes types

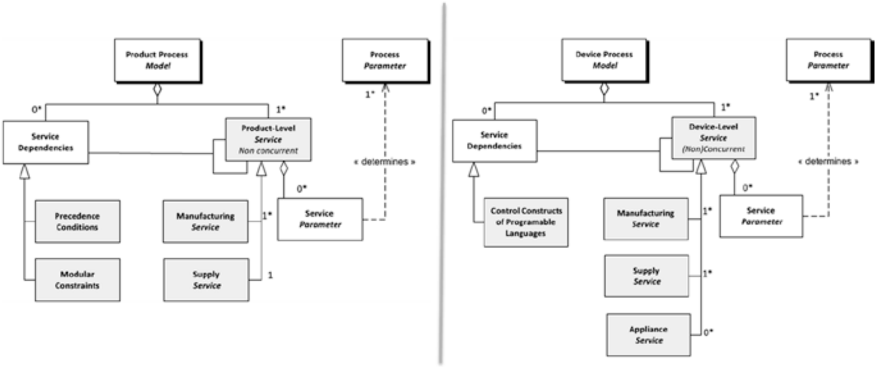

Fig. 3 Product- and device-process models

can in turn represent other composite processes and so on until having just atomic services.

In Fig. 3 the conceptual model can be seen for both types of composite processes namely: *Product-Level Processes* and *Device-Level Processes*. Such models where designed taking as reference the required production information of a product specified by the standard ISA SP-95 [21]. However, its information was readapted and clustered for the convenience of product driven systems with customized products. These models correspond to the production recipe of a given product family whose production order is offered as a supply service. Both models are formed by a collection of workshop services, describing the required manufacturing operations, and a collection of service dependencies which describe the relations between the services which actually describe the structure of the process. Each service in the process possesses a collection of service parameters needed for its execution which is determined out of the higher order process parameters.

As seen in the last section, the main difference between these two models relies in the concurrency characteristic of the composing services. Such difference becomes tangible in the specification of the process structure i.e. dependencies among services.

In a Product-level process dependencies are stated with a *predecessor perspective* with a table of precedence conditions i.e. what services need to be executed before a given service. In a Device-level process, dependencies are more complex due to their to their more tight relationship thus these are suggested to be represented through control constructs found in programmable languages with an event-driven approach.

3.3 Process Specification Framework/Walkthrough

Now that the conceptual models of both processes and services have been presented, Fig. 4, describes the product specification process.

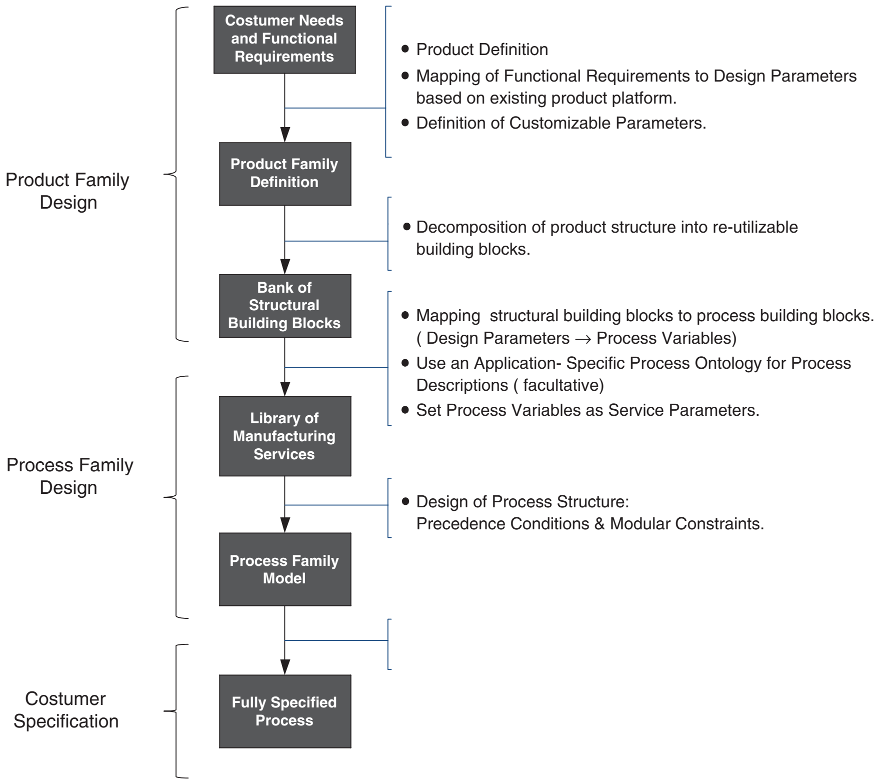

Fig. 4 Process specification design

It describes the steps from the definition of customer needs and functional requirements all the way up to the definition of a Process Family Model to be ready to go through the specification of customizable parameters. The application of these steps for the creation of the process model for each of the products declared in the system will lead to the construction of a library of manufacturing services based either on an application-specific ontology or on a unified domain ontology, as that presented in the German standard DIN 8593 [22] for assembly processes.

4 Conclusion

This work describes a framework for the specification of manufacturing processes implemented in distributed systems based on the web-services whose application in HMS gives rise to a new paradigm: Service-oriented Holonic Manufacturing Systems (SoHMS). The methodology identifies different types of manufacturing services namely: Product-level, Device-Level and Atomic processes. For each one, a process model is proposed describing its composition and structure. A manufacturing-service model is also proposed by describing its composition. Both models allow the description of fractality at product level and at process level. Moreover, the capability of resources can then be described by their offer of workshop-services, more than on their internal model. This facilitates the introduction of different resource technologies as manufacturing-service descriptions are independent of the technologies or methods used for their implementation. Future work will concentrate on adding flexibility to the SoHMS through the creation of an orchestration model and engine that will allow the scheduler to explore the other valid sequences that will bring the system closer to an optimal point.

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Aligning Decision Support with Shop Floor Operations: A Proposal of Intelligent Product Based on BDI Physical Agents

Pablo García Ansola, Andrés García and Javier de las Morenas

Abstract MAS models have the drawback of an excessive dependence on up-to date field information and on complex interaction protocols. This work proposes a theoretical and experimental agent-based Decision Support System (DSS) architecture that is designed and developed to align shop floor operations, but including the Radio Frequency Identification (RFID) information feedback. Based on these automatic product feedbacks generated by the RFID visibility frameworks, the proposed Multi-Agent System (MAS) allows defining a competitive space where intelligent products negotiate by using their own knowledge and global/business constraints. Specifically, this product-driven MAS has been structured on a split organization model to enforce the idea of division between physical elements and "Information and Communication Technologies" (ICT). This division into two platforms simplifies the design, the development and the validation of the MAS in shop floor environments, providing a higher level of abstraction and preserving the independence between platforms. The proposed MAS framework, called MAS-DUO, has been tested in the ground handling operations at the Ciudad Real Central Airport and in a simulated logistics centre at the Autolog Labs-UCLM. This paper introduces the BDI physical agents of this framework as the core of this new approach, a new vision that mixes Beliefs-Desires-Intentions (BDI) reasoning, RFID and the Markov Decision Process (MDP).

P.G. Ansola · J. de las Morenas (✉)
AutoLog Group, Almadén Mining and Industrial Engineering School,
University of Castilla-La Mancha, Almadén, Spain
e-mail: javier.delasmorenas@uclm.es

P.G. Ansola
e-mail: pablo.garcia@uclm.es

A. García
AutoLog Group, School of Industrial Engineering, University of Castilla-La Mancha,
Ciudad Real, Spain
e-mail: andres.garcia@uclm.es

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Keywords BDI · Physical agents · RFID · DSS

1 Introduction

Given the actual high level of the operational disaggregation in worldwide companies, management staff needs to drive their business decisions to a common point of view where all their parts support the global objectives of the company. This necessity of integration brings forward concepts such as alignment that has become particularly important in the field of business integration and interoperability. Luftman et al. [1, 2] point out that firms need to align their Information System (IS) strategies with the rest of strategies in the business. Henderson and Venkatraman [3] developed a strategic alignment model using two dimensions: the strategic integration and the functional integration, taking also into account what they call cross-domain. Camponovo and Pigneur [4] suggested the necessity of three levels to make possible the complete alignment of the IS. The first one is the strategic alignment, related to the internal configuration between the IS and the enterprise components. The second level, which is aligned with the environment, takes into consideration external disturbances [5]. Finally, the third level deals with how the system has to evolve over the time in order to maintain the alignment.

These new *alignment concepts* use technologies coming from distributed artificial intelligence, and specially propose their application in order to achieve environmental alignment. On one hand, new interaction protocols can face the strategic alignment. On the other hand, the environmental alignment is achieved by getting an accurate picture from the environment; this information needs to be up-to-date and linked to the physical world through trace and tracking services. Many industries can benefit from the advantages provided by alignment; the case of airport operations is one of them. These operations involve the cooperation of international regulation bodies, private companies, airlines, aircraft operations and airport operators, all of them in the same decision process but with common and individual objectives; this situation presents a decision making process hard to align, especially when disturbances occur [6]. At this point, new concepts as "Internet of things" are dealing with the information generated by these disturbances, the objective of "Internet of things" being to automatically capture the information of products when new events occur. The next subsection details this vision and the involved technologies.

1.1 Intelligent Product

In practice, the environmental alignment requires effective methods to access the external and internal surrounding information. This information feeds the internal beliefs of the distributed intelligent units that compose the heterarchical control. In the manufacturing research community, as a new logic interface between components, the service vision arises as a tool to provide a dynamic access to information between modules [7]. The most important example is the new "Internet of Things" vision, which provides new mechanisms based on virtualization of physical resources to provide services between the real world and the computers [8]. "Internet of Things" virtualizes every physical thing in this world, which can also become a computer that is connected to the Internet. The "Internet of Things" adds another data dimension, it allows the physical world, things and places, to generate data automatically; it is about sensing the physical world [9]. These smart things communicate among each other and with computers in a machine-to-machine way on Internet. However, it only recently became relevant to the practical world because of the progress made in hardware developments that have taken place in the last decade. Once the physical world can include software avatars, an essential research is to apply this vision to the shop floor in order to integrate the virtual and the physical parts of the products in a logical unit which is called intelligent product. In the next list, Wong [10] enumerates the requirements to define a intelligent product:

- The product possesses a unique identification.
- The product is capable of communicating effectively with its environment.
- The product can retain or store data about itself.
- The product deploys a language to share its features, production requirements and plans.
- The product is capable of participating in relevant decision-makings to its own destiny.

Therefore, this intelligent product presents autonomous capabilities and services to the rest of shop floor elements in a flexible way to define plans; the intelligent product can be the logical unit that builds the required heterarchical control. The intelligent product service-oriented approach provides a way to create a new architecture that reflects products as components providing autonomy and heterogeneity features. These autonomous services help to manage human control activities related with assets, spare parts, tools and their relationships during the product lifecycle. In this vision, the humans delegate the control activities to the smart products, which qualify their functionalities as services. It increases the return on investment based on an organisational agility and interoperability, because it allows dynamically discovered functionality with minimum coupling [11]. Besides, the service-oriented approaches allow loose coupling between technologies and underlying applications, which is useful in the manufacturing environment because of the heterogeneity of elements. From a distributed manufacturing point of view, when the product takes the initiative during the plan, production is known as product-driven [12]. This shop floor control is a service approach where the products search and compete for services to assist them during the production process along the life cycle.

The division in functional product intelligent units at the shop floor operations can achieve agility and flexibility requirements, but a dynamic interface with physical resources needs to be addressed at the shop floor.

An extended review of the state of the art in intelligent products can be found in the work of Meyer et al. [13] and at McFarlane et al. [14].

2 Layering the Agent-Based Control to the Current Shop Floor Needs

Several problems in the implementation of the MAS vision in the real environments have been detected by a number of authors [15]. Marik and MacFarlane [16] enumerate more than a few barriers, such as the cost of the investments, the operational guarantees, the performance, the scalability, the commercial platforms and methodologies, the engineering education, and the unclear standards. Currently most of the previous barriers are closer approached with the existing standardization organizations as FIPA [17], the existing methodologies systems as JADE [18] or commercial solutions as JACK [19]. Then, more recent approaches as those proposed by Leitão [20] have detected that the demand of companies requires control solutions as proven products integrated with the existing elements. This requires a new way of thinking in order to be able to reconfigure MAS as an interoperable and pluggable system, not only deployed as a unique solution to each problem. Other barriers detected by Leitão are the necessity of supervisory tasks that provide robustness, the interoperability based on ontologies or the hardware integration. In this line, and in order to foster the emergence of MAS, Lopez [21] highlights robustness and control as key points to integrate MAS as usual, since the independence of agents tends to make the control of the system output difficult to predict

Among these well-known problems recognized by the research community, during the interview with the IT staff during the definition of the requirements in analysed scenarios such as airports or distribution centres, the software and hardware companies involved were reluctant to integrate the system as a whole product scheduling, which is the most common approach defined by MAS/Holon researches. In the situation of a unique system, the roles of companies need to be fixed, in terms of modelling, responsibility and management. The companies directly rejected a unique global system; they put forward that there are not business interest in a whole integrated IT product in shop floor operations. Therefore, this work detects that the minimum possible hierarchical control requires at least two horizontal layers with the same level of importance in real scenarios, in which the decisions and responsibilities are split. On one hand, the first system is the high-level information system that is currently called business intelligence, and is composed by software modules such as: Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), Warehouse Management Systems (WMS), Retail and Point-of-Sale (POS), etc. Most of them correspond with a soft centralized information system having a database that receives external data like orders or customer constraints which directly affect the product scheduling. Some existing well-known companies with different proposals in this line of solutions are: SAP, Oracle, Navision, SITA or SAGE. On the other hand, there are information processing requirements more closely related to the specific devices and the hardware of the company such as PLCs, robots, CIMs, CNCs, machinery, etc. This hard information directly affects the product scheduling with physical constrains and field layouts.

The design of manufacturing MAS of a whole control system is a clear barrier in order to provide agent-based decision-making in the companies. The system as

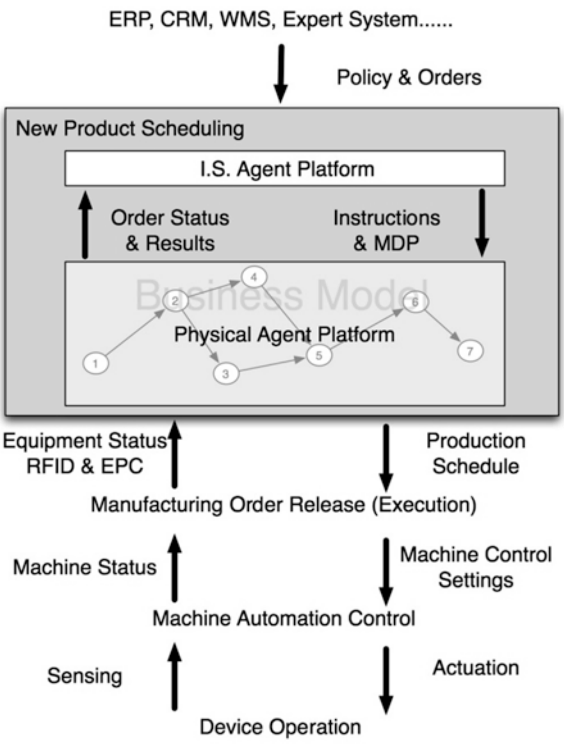


Fig. 1 The MAS-DUO proposal: the new product scheduling

a whole has not yet been able to increase the interest of manufacturing IT providers because it is very hard to maintain and develop as it involves a broad range of technologies. Therefore, based on previous handicaps, a horizontal layered MAS acting as a new product scheduling system seems adequate with the current requirements instead of a unique agent platform, but a full design and validation process needs to be addressed. Figure 1, based on the manufacturing control, details the layering of the product scheduling system. This layering proposes a division of the agent space into two platforms for being able to fully implement these MAS in the current manufacturing/logistics scenarios.

Therefore, this work introduces an adaptation of the holonic concept into two separate levels which are developed by using agents. The research community addresses Holons as logical units with hardware integration but real implementation problems arise. The next chapter details the new BDI physical reasoning in order to provide an algorithm to divide Holons into different logical units [22]. The first platform is an agent structure related to the physical elements of the plant and directly connected to the physical world, which is called "Physical Agent Platform". The second platform is an interface with the upper information systems of the company, which is called "IS BDI agent platform". This idea comes from the Holon concepts of communication in manufacturing control using a service-oriented division based on protocols and decision-making techniques instead of a unique Holonic structure incorporating these two expert systems.

3 Physical BDI Agents: A Proposal of Intelligent Product

Physical BDI agents can be directly benefited from visibility frameworks through a software interface, which in the case at hand is the standard EPCIS. The EPCIS specification helps the definition of this dynamic interface by using the existing services, which automatically publish the real-time information coming from the plant and its circumstances, reporting treated information and abstracting upper IT levels. From the BDI point of view, a well-formed reasoning requires a constant information feedback from the environment to constantly feed their beliefs. MAS-DUO [23] proposes the EPC subscriptions to connect the physical products/resources with the internal reasoning of the affected agents; the beliefs of these agents are updated through the standard EPCIS XML specification. The junction of BDI and EPC in the Physical BDI agents constitutes a Procedural Reasoning System (PRS) with an actualized RFID event database. It is a framework for constructing real-time product-driven reasoning, which can perform decision-making in dynamic shop floor environments. The states of the product are defined and detected by the "Where?" (Read point) and "Why?" (Business step) EPC information. In the next Eqs. (1)–(4), p represents the products which have a set of Reader Points (RP) and Business Steps (BS). If there are more business steps and read points, the precision during the decision-making is bigger because of the corresponding increase in the number of states. The definition of states is flexible, so new read points and business steps can be added during operations.

$$ReadPoint(p) = \{RP_1, RP_2, \ldots RP_n\} \tag{1}$$

$$BusinessStep(p) = \{BS_1, BS_2, \ldots BS_m\} \tag{2}$$

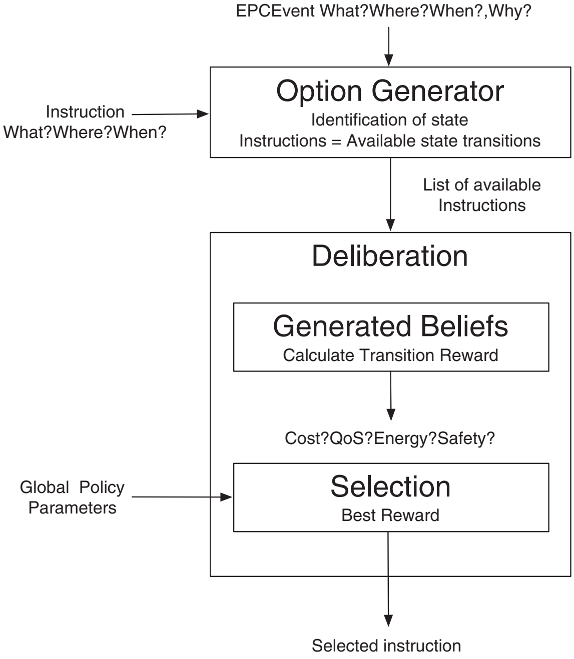
$$States(p) = \{RP \times BS\} \tag{3}$$

$$States(p) = \begin{bmatrix} S_{00} & \cdots & S_{0n} \\ \vdots & \ddots & \vdots \\ S_{m0} & \cdots & S_{mn} \end{bmatrix} \tag{4}$$

Once the states are identified by using a simple inference of BS and RP, the current state (S) of the product and the desirable state (S') define the transactions between states S → S'. The full transitions do not have to be direct so as to take place in only one step; there can be intermediate states, which have to be identified during the reasoning process. This is the definition of task, which means the sequential definition of states until the goal state (S_n) (5) in which every instruction corresponds to a unique state transition. In the problem at hand, there are available technologies to solve state transition problems as is the case of MDP techniques, but any such solution needs to be integrated into the BDI reasoning process. The objective of these techniques is to obtain the best transitions from the product state S to the product state S' depending on configurable rewards.

$$Task(p) = \{S_0\, S_1\, S_2\, \ldots\, S_n\} \tag{5}$$

Fig. 2 The deliberation process in the physical BDI agent



The BDI reasoning process of each agent has to select its intentions by using these new generated beliefs while looking at the current state. This really supposes a BDI customization in the physical agent; Fig. 2 details the situation of the Physical BDI agents that need to pick up information from the EPCIS, update their beliefs, generate the new beliefs and select the best reward.

Combining the BDI and MDP techniques, the internal beliefs situate the agent in one of the defined states in the MDP. The intentions of the agent define the actions that will define the state transitions; they allow the generation of a plan based on the Markov parameters depending on the weights of the rewards. The desires are the goal states or final states in the MDP that the agents try to reach. Therefore, there is an internal MDP in each physical agent which chooses the actions with the maximum reward trying to reach the goal state. The reward function of the MDP can be customized to the needs of the company, which can be based on the importance of the delays, on the costs of the process, on the importance of the clients, on the power consumption or on a mix of all. In the proposed scenarios, the reward function only depends on the value of 4 parameters defined by the involved company but needs to be adjusted. The average reward is defined as the limit of the sum of rewards divided by the number of states, in order to not unbalance the weight of the rewards (6).

$$\begin{gathered} R(s,s') = A\,Time(s,s') + B\,Cost(s,s') + C\,QoS(s,s') + D\,Energy(s,s') \\ \text{Limit Reward} = \lim_{\mathrm{T}=1}^{\mathrm{S}} \frac{\sum_{\mathrm{t}=1}^{\infty} \mathrm{R}^{(\mathrm{t})}}{\mathrm{T}} \end{gathered} \tag{6}$$

Looking at the global decision parameters of the company, if the firm wants to reduce costs, it will increase ‘B’ to give more importance to the cost in every single action instead of focusing the actions into reducing the delays ‘A’ or into improving customers satisfaction (i.e. service level) ‘C’. With a correct customization of the parameters, the company can define a dynamic decision policy to be followed in its operations.

4 Results: A Proposal of Intelligent Product Based on BDI Physical Agents

This definition of Physical BDI agent achieves the second level of product intelligence as defined by the Auto-ID labs [24], which provides these features:

- *It possesses a unique identity*, which is achieved through the uses of the EPC subscription services that define direct communication with specific products/resources. This also goes in the way of the “Internet of the Things”; the Physical BDI agent allows defining a decision-making avatar of the products.
- *It establishes an effective communication within its environment*; in this case, the Physical BDI agent provides negotiation protocols to compete for products and resources in a non-hostile communication area.
- *It stores data about itself*; the EPC subscriptions send to the agents the information about the product, and even new beliefs are generated during the BDI reasoning such as cost, energy or quality of service.
- *It deploys a language to display its features or production requirements as services* to the rest of shop floor elements. FIPA provides interaction protocols able to publish and share information to subcontractors in a standard way.
- *It participates in making decisions relevant to its own destiny*. The own knowledge of the agent can balance the decision-making by itself and the presented reasoning process supposes enough independence to select its best options. As well as, the decisions are also be supervised by a global policy in order to maintain a decision alignment in this high distributed environment.

5 Conclusions

The proposed Physical BDI agent system is a suitable option in the implementation of a product-driven control, in which products and resources start and launch instructions in a distributed decision space. The product-driven control makes it possible for manufacturing companies to meet business demands more quickly and effectively. The products interact along the decision-making process by using their gained knowledge and specialization, which make for a really distributed and flexible process. Even more, the Physical BDI agents can start or drive the interaction protocols with the rest of elements and plan the allocation of resources during their production or delivery. This is the core of the product-driven negotiation, in which the products, only looking at their internal beliefs, trigger the control. For example, if a mixed pallet needs to be ready at a specific time, the instructions will start when the pallet agent considers it by using its BDI reasoning. These low-level actions taken by the Physical BDI agent define a plan in a competitive coordination; where these reactive actions have a permanent dependency on the state of the products. This plan is independent of the upper information systems but can be driven by it through using global decision parameters.

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Part III

Distributed Modelling for Safety and Security in Industrial Systems

Integrating Risk and Hazard and Plantwide Control Solutions for Reconfigurability

Radu Dobrescu and Gheorghe Florea

Abstract The technology in process control has been changing towards full control and management systems including Safety Instrumented Systems (SIS) and security middleware. Modern goal is to keep the functionality of the process even at less performance, proposed solution implementing risk and hazard control paradigm. An architectural oriented approach is the base to develop advanced control integrated architecture open to incorporate reconfigurable control. The main achievements of authors work are: a new approach to define control, integration of control and prevention in control strategies, plantwide control viewed from holistic approach, a new hierarchical structure of control and safety and a framework for reconfigurable control development.

Keywords Process control · Risk and hazard · Hierarchical system architecture · Reconfigurability · Safety instrumented systems

1 Introduction

There are a lot of research efforts dedicated to reconfigurability in manufacturing with a lot of successful methods, algorithms and projects. In the process industries despite the fact that a shut down costs millions there are not much approaches maybe because of complexity and important financial efforts.

In order to react to the unpredictable changes in product variety and in process technologies, reconfigurable systems allow the adjustment of production capacity and functionality by rearranging or changing their modular components. This paper explores the potential of the reconfigurability feature to be the base for developing

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R. Dobrescu (✉)
Politehnica University of Bucharest, Bucharest, Romania
e-mail: rd_dobrescu@yahoo.com

G. Florea
Society of Systems Engineering, Bucharest, Romania

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a new strategy to handle out-of-the-ordinary events in the process, maintaining production flow when breakdowns occur. Decisions regarding how to deal with exceptions to the production process are complex and depend on the process system configuration and on performance and economic variables. The authors have proposed to consider the *Risk and Hazard Control* (RH Control) model in a previous work [1] as a basis for developing adequate strategies to avoid the effect of extreme events, because of its ability to be very agile, as well as being reactive and efficient.

RH Control is not only a new paradigm of our area but is one of the most important issues to implement efficient solutions. Our target is to show that an architectural oriented approach is able to develop advanced control integrated architectures open to incorporate reconfigurable control. Our analysis shows that all diagnosis methods must be used in order to identify the risk. Usually safety, reliability, quality, efficiency and robustness of control have been regarded as the main requirements in process automation. However, this paper is motivated by adaptation to different types of changes. Reconfigurability means the capability of the automation system to adapt to process configuration changes. But the benefit of the reconfiguration capability is limited if there is lack of redundancy in the lower-level automation system and the controlled process. For this reason we recommend the global approach of the *plantwide control* to avoid fault propagation interdependencies due to multiple interacting unit operations. What sets this approach different from previous ones is the possibility to include both discrete and continuous control operations in the reconfiguration process. Applications designed as distributed planning of control sequences and distributed iterative search of values for supervisory control variables are proposed as means to handle both planned and unplanned operational change situations. The distributed iterative search process can be used to find new values for a set of control variables. If operational change situations can be handled with these methods then the applications can facilitate flexibility and responsiveness and become dependable.

2 RH Control—The New Challenge

2.1 Control and Strategy

The requirement of improved reliability, efficiency and maintainability during process operation brings more challenges to the process control design. Traditionally, the prime control objective has been to maintain desired process performance while ensuring robustness against process disturbances. With such design system, in the event of critical faults the complete control performance can either deteriorate significantly, or may even collapse. It is well known that customer requirements must be translated into design specifications for products and services. Specifications include design optimums or targets, as well as limits which define the minimum or maximum of given characteristics that a company wishes to deliver to its customers.

“Control” was originally, from technical point of view, a controversial term mainly due to the ambiguity of objectives subsumed, including the following: to exercise restraint or direction over; dominate, regulate, or command.

Later, the term has been used extensively to define “Activities involved in ensuring a process is predictable, stable, and consistently operating at the target level of performance with only normal variation”. Recently, Petrovich [2] makes an important step to a modern approach to control definition: “a new definition of process control must be closely aligned with traditional meanings of control but must include the demands of quality”.

In this paper we aim to redefine the “process control” paradigm, including a new way to look at control, new methods of process evaluation and control strategies. This approach provides assurance that RH control design meets the intended needs of customers, the quality goals to eliminate non-conformance and minimizes variation around appropriate targets, at minimum cost.

The purpose of RH control strategies is the achievement of these goals. Control Strategy is a planned set of controls, checks and sequences, derived from current product and process, having the target to assure process performance and product quality. The controls can include facility and equipment operating conditions, product specifications, in-process controls, process parameters, attributes and circumstances related to risk and hazard and the associated methods, frequency of control monitoring and control compliance. Therefore, RH control is the ability to constrain process variation and prevent non-conformance over time, maintaining the stability and functionality even in hazard and risky situations.

2.2 Safety and Security

Safety is an important issue nowadays that received an increasing amount of focus lately. The reasons are, unfortunately, the numerous accidents occurred in industry plants which require the process industry to take a hard look at current practices like process design, process control, risk analysis and control, risk assessment.

The requirement of improved reliability, efficiency and maintainability during process operation brings more challenges to the process control design. Traditionally, the prime control objective has been to maintain desired process performance while ensuring robustness against process disturbances. With such system, in the event of critical faults the complete control performance can either deteriorate significantly, or may even collapse. Integrating safety and security with control provides multiple benefits to end-users:

- Minimize intervention and shutdowns and recover more easily from process upsets
- Easier integration of components and systems
- Reduce hardware and installation costs
- Minimize the quantity of spare parts that need to be kept on the shelf
- Easy configuration with preconfigured function block selections

- Easier engineering and maintenance for one system
- Removing the need to implement and support multiple networks
- Reduce number of security tools and devices
- Reduced training requirements
- Improved accessibility and remote support

Even for integrated safety and security systems with process control, there is a necessity for more than a Safety Instrumented System (SIS) to maintain the process running even with less functionality instead of shut down. The role of a SIS is to provide a safety-related function in order to monitor and maintain the safety of any equipment under its control.

According to the IEC 61511/ISA 84 process safety standards, the process risk has to be reduced to a tolerable level as set by the process owner. The solution is to use multiple layers of protection, including the basic process control system, alarms, operator intervention, mechanical relief system and a SIS.

The Basic Process Control System (BPCS) is the lowest layer of protection and is responsible for the operation of the plant in normal conditions. If BPCS fails or is incapable of maintaining control, then the second layer, Operator Intervention (OI) attempts to solve the problem. If the operator also cannot maintain control within the requested limits, then the SIS Layer must attempt to bring the plant in a safe condition. Based on the introduction of a new decision level-Risk and Hazard Control and a new state of the process- safety state, the layers of protection and also the impact over the process are changed accordingly (see Fig. 1).

RH Control is a new approach aiming to solve this by building a new architecture that addresses decision support for near critical situation management in continuous process industries. In particular, assistance in terms of diagnosis and solutions is provided to the plant and/or to the staff when situations suitable to be corrected, prevented or enhanced are detected. The goal is to conduct the process

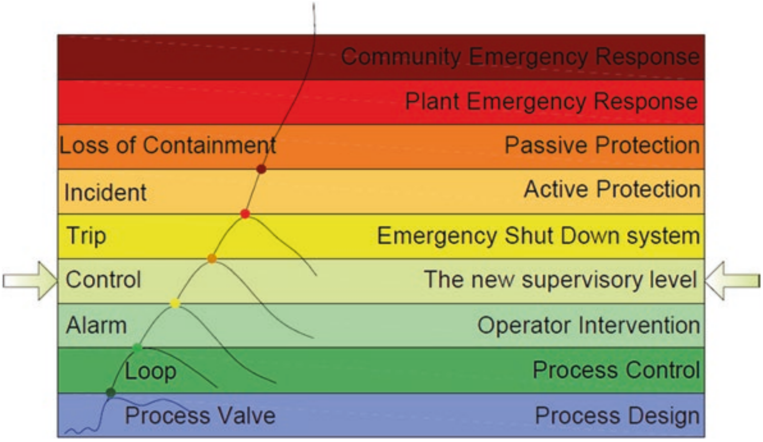

Fig. 1 Layers of protection and impact on process

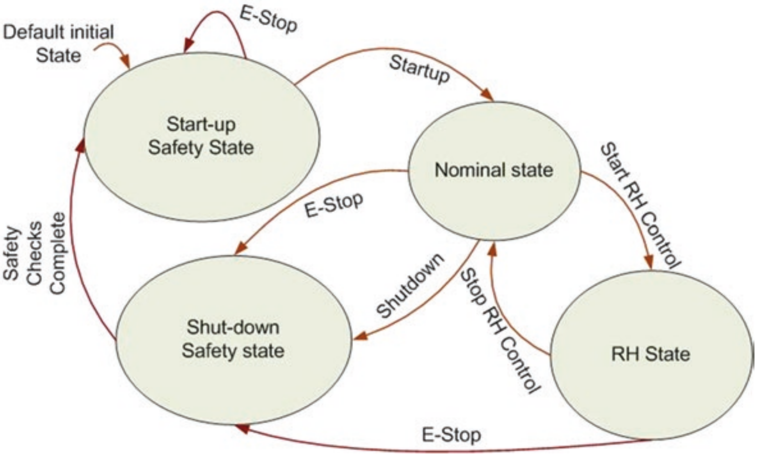

Fig. 2 Process states

to the safety state by RH control strategies [3]. Figure 2 illustrates the process state diagram.

RH State is a provisional process state introduced for a very short time if the control strategy is not able to maintain it and the shutdown is inevitable. If in this interval RH control is successfully performing, after some time the process can be driven to the nominal state.

3 Reconfigurable Control—State of the Art

There are a lot of research efforts dedicated to reconfigurability in manufacturing with a lot of successful methods, algorithms and projects. In the process industries despite the fact that a shutdown costs millions, there are not many approaches maybe because of the complexity and big financial efforts. Component reconfiguration applied to controller, actuator and sensors is the main target to achieve new solutions and performances.

New approaches to design static and dynamical reconfigurable control systems are proposed based on the eigenstructure assignment techniques. In order to guarantee the stability of the reconfigured closed-loop system in the case of output feedback the methods conduct to the recovery of nominal closed-loop performance after a fault occurrence in the system, in the state and output feedback designs.

Wang et al. [4] have investigated the design of reconfiguring a class of linear control systems via state feedback eigenstructure assignment. The design aim is to resynthesize a state feedback control law such that the eigenvalues of the reconfigured closed-loop control system can completely recover those of the original closed-loop system, and make the corresponding eigenvectors of the former as close to those of the latter as possible.

Steffen [5] introduces structural analysis as a tool for reconfiguration. Because a fault changes the structure of the system, the reconfiguration solution is sought on a structural level. Reconfiguration, an approach for fault-tolerant control, involves changing the control structure in response to the fault, and was extended in the work with the idea of the so-called virtual actuator approach.

Manuja and Srinivasan [6] propose a reconfigurable control structure implemented using supervisory model predictive control (MPC) formulation to ensure uninterrupted process operation in the event of individual loop failures associated with the base control system. The proposed fault tolerant control architecture includes process monitoring, diagnosis and recovery blocks.

Model predictive controllers are presented also in [7], based on dynamic models of the process, most often linear empirical models obtained by system identification. MPC models predict the change in the dependent variables of the modelled system that will be caused by changes in the independent variables, using: the current plant measurements, the current dynamic state of the process, the models, and the process variable targets and limits to calculate future changes in the independent variables. These changes are calculated to hold dependent variables close to target while honouring constraints on both independent and dependent variables.

In recent years, support for transparent dynamic reconfiguration has been added to middleware platforms, shifting the complexity required to enable dynamic reconfiguration to the supporting infrastructure. In [8] an approach is discussed to dynamic reconfiguration of distributed applications that is suitable for applications implemented on top of different platforms, based on an independent view of an application that profits from reconfiguration transparency.

Even if those impressive results in different applications have demonstrated the importance of this road there are a lot to do in the near future. Two main directions must be taken into consideration: (1) Fault identification and diagnosis and (2) Reconfigurability design.

One of the main approaches is to incorporate fault recovery mechanism into the controller design so that faults critical to process operation are handled in a systematic manner rather than through ad hoc corrections. Fault identification must take into consideration various methods and techniques, but not limited to: autotest, parameter value validation, correlated parameters analysis, process contextuality, trends, exploratory data analysis (EDA), confirmatory data analysis (CDA), behavioural analysis, simulation, expert systems, intelligent agents [9, 10].

One of the first proposals for an architecture based on reconfigurability design is that of Chokshi and McFarlane [11] which uses the coordinating function to monitor and control local planning, local optimizer and local control. Based on this concept several platform-specific realizations were developed, satisfying the requirements on the ability to reconfigure components and structure, expressed in an abstract manner or in functional manner. The most known on the market are: Business Frameworks, Architecture Frameworks, Programming Frameworks, Project Management Frameworks and Industry Operations Frameworks.

4 Plantwide Control

The control application for to processes still needs to be adequately addressed because the target is oriented not only to parameters control but more on improving overall plant operability by minimizing plant down times. The challenge involves plantwide nature of the problem itself with inbuilt fault propagation interdependencies due to multiple interacting unit operations, product recycle, and risk assessment. Systems and their properties should be viewed as wholes, not as collections of parts, because function as wholes and their functioning cannot be fully understood solely in terms of their component parts.

Plantwide control is a holistic approach concerned with the structural and functional decisions involved in the control system design of a processing plant.

The main goal of plantwide control design is to find a set of measurable parameters, a set of inputs that can be manipulated and a set of controlled variables which, when kept at constant set points, indirectly lead to near-optimal operation with acceptable loss. Since the economics are determined by the overall plant behaviour, it is necessary to take a plantwide perspective.

Most available control theories assume that a control structure is given at the outset. There are two main approaches to the problem, a mathematically oriented approach (control structure design) and a process oriented approach presented in [12].

Because designing a control system for complete plants is a large and difficult task, to solve the problem the designer will try to decompose the problem into manageable parts based on one or more decomposition approaches.

The process of designing control systems usually imposes many demands on the engineering team. These demands often emerge in a step-by-step design procedure; even if all this steps are appropriately applied to classical design, in real life the operation is based on different situation including risk and hazard. A generic methodology to perform hazard analysis, relating to the management of the dependability, includes the following steps:

- Specification of the applicability (program/project/data/constraints/personnel).
- Identification of the hazards (expert opinion/lessons learned/test data/technical analysis/hazard analysis).
- Evaluation of the consequences (impact/severity, probability, timeframe).
- Risk assessment (resources/leads/project; metrics information, risk management structure).
- Monitor risk metrics and verify/validate mitigation actions.
- Monitor risk decision effects.
- Checking of the real scenarios and the progressive updating of the information.

In this process it is necessary to classify the functions according to their severity, then to be able to analyse them according to their *Safety Integrity Level* (SIL), and if necessary, refine the hazard covering method s.

Depending upon the failure type, a typical control problem reformulation would involve one or more the following tasks:

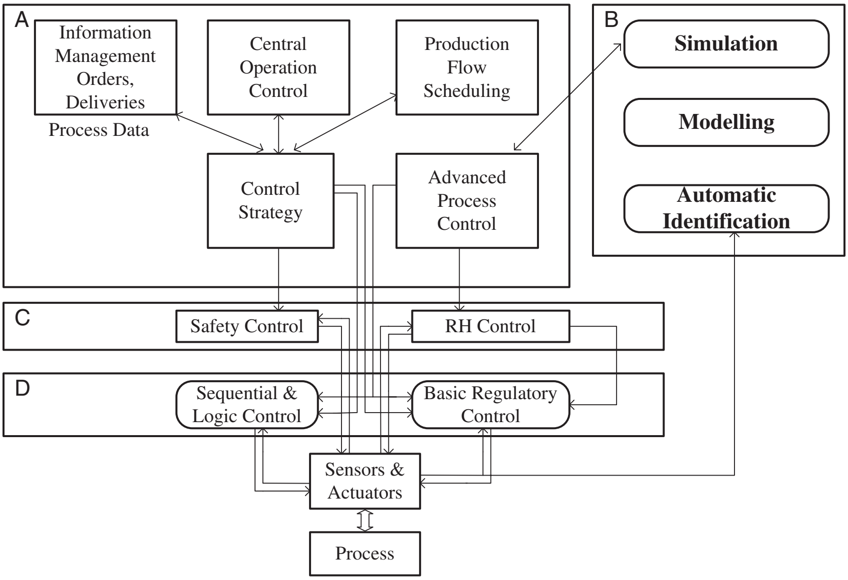

Fig. 3 Control and safety architecture

1. Modifying set-points.
2. Redefining constraints/limits.
3. Changing the internal model to reflect the fault condition.
4. Changing the control strategy according with safety state.

The results are taken in the design of the process control architecture. Integration of RH control able to maintain the process in the safety state with control hierarchy layers is shown in Fig. 3, where A, B, C, and D suggest a holonic organization at several levels.

The four main holons are, from the upper level: D—classical control based on basic regulatory, sequential and logical, C—safety level based on safety instrumented systems (SIS) and the new paradigm RH control, B—remote level based on internet or cloud able to do automatic identification, modelling and simulations, A—management level, which has two main functions: management and supervisory control [13].

To be able to perform such tasks the system architecture, structure and data flows must be able to support different methods of reconfiguration. Consequently, reconfigurability design must focus on: (i) Components (Sensors, Actuators, Controllers, Configuration); (ii) Control (Algorithms, Structure, Data flows, RH control strategies, Integrated control); (iii) Process (Equipment, Flows, Process, States).

5 Reconfigurable Control Architecture—Design and Applications

Advances in software technology have the potential to revolutionize control system design and implementation. Component-based architectures encourage flexible "plug-and-play" extensibility and evolution of systems. Distributed object computing allows interoperation; dynamic reconfiguration is feasible based on technology and standardization advances enabling the evolution of systems while they are still running. Technologies are being developed to allow networked, embedded devices to connect to each other and self-organize.

To develop a framework for control system design we propose the architecture presented in Fig. 4.

The framework is able not only to host the entire process control system (hardware, software, application, operator and engineering interfaces) but also the model, even simplified, of the process, the simulation features, a library of algorithms and strategies, and case studies. Any suitable monitoring and diagnosis technology can be used for the nominal functioning values. The focus in our work is

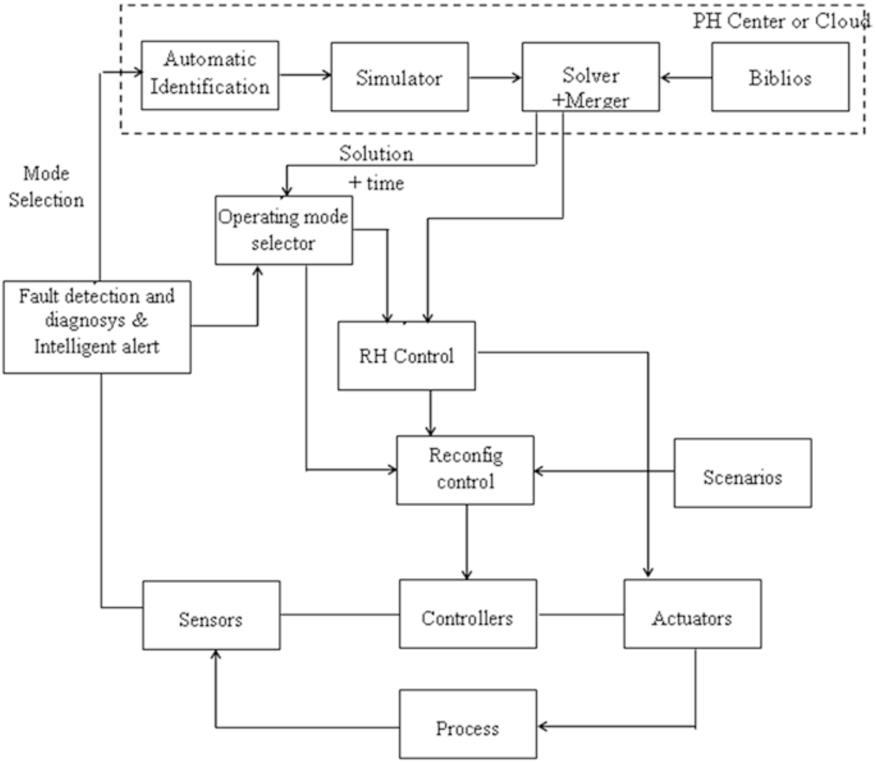

Fig. 4 Reconfigurable control development framework

on developing a structure of fault detection and intelligent alert that, in conjunction with RH control, can conduct to the recovery of functionality even with spoiled performances. Mode selection part of this structure functions as follows: At first, the fault recovery measures for individual loop failures are derived from a fault impact analysis. Next, the fault recovery principle initiates a change in the operating strategy of the plant by incorporating changes in the operating factors associated with failures in the model based control calculations. This strategies can be implemented with direct commands from RH Control or/and associated with reconfiguration scenarios. Among the achievements obtained using our RH Control architectural framework and methodology, two of them were implemented and proved significant performance: PH Center and BIBLIOS.

PH Center [14] was developed to host applications with high level of risk like ESD-emergency shutdown systems, Fire and Gas systems, BMS-burner management systems remotely.

BIBLIOS [15] is a library for reusable algorithms developed mainly to host control and check algorithms and strategies for applications.

The control solutions are obtained in PH Center or/and on "cloud" where there are modules for automatic identification, simulations, solver and merger but also algorithms and strategies hosted in BIBLIOS. Results obtained are stored in a decision table and translated by the supervisory module for implementation over the base control system in the event of failures. The new developed reconfiguration schemes and strategies enable the plant to continue to be operated safely (even at lower performance levels) and avoid its shutdown.

6 Conclusions

Risk and Hazard Control is the new paradigm of automation, aiming to help in this improvement by building a new architecture and a distributed and generic software system that addresses decision support for near critical situation management in continuous process industries. In particular, assistance, in terms of diagnosis and solutions is provided to the plant and/or to the staff when situations suitable to be corrected, prevented or enhanced are detected.

The focus is on new algorithms and strategies for the integration of different software components as well as on the system architecture itself. These software components include core modules, user interface modules and problem solving modules. RH Control follows the conceptual structure of most distributed control systems that is a multi-layered heterarchical (holonic) structure which ensures complete distribution of knowledge and decision-making among holons without reliance on any central control unit. The complexity of the control mechanism increases in higher layers. All the basic functionalities of the system are grouped into problem solving components that work in a cooperative way to find a solution to the plant problems or to optimize the plant objectives. These applications include the following functionalities at different control layers:

Strategies: Management of global objectives of the plant and their interrelation (management of maintenance operations, incident prevention, risk and hazard control, assessment of production costs in real time, loop tuning optimization, quality deviation detection and alarm management).

Tactics: Assistance through the problem life cycle, including process failure prevention, risk detection and diagnosis, control and strategies.

Operations: Tasks such as filtering and validation of plant data, variable estimation and trend forecasting are complementing with reconfigurability.

Further work will be focused on the implementation of RH Control modules, using an aggregate of intelligent technologies which include: the Service Oriented Architecture (SOA) approach based on Web Services, the cooperative and consensual Decision Support Systems and the Multi-Agent System paradigm, with the particular Holonic Multi-Agent System architecture.

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Wireless Holons Network for Intralogistics Service

Patrick Pujo, Fouzia Ounnar and Tarik Remous

Abstract This paper continues our previous research works on holonic and isoarchic control solution for manufacturing systems control based on the PROSIS model, this time considering WSN technology as support for new opportunities of flexibility, security and performance for production systems. First, the objectives are addressed. The WSN technology allows the association of a decision-making capacity to each physical entity of the production system. An application to an intralogistics service in a Job Shop is presented. New opportunities for intelligent control of production systems are highlighted.

Keywords Holonic control · Isoarchy · Intralogistics · WSN · WHN

1 Introduction

The control of manufacturing systems is subject to increasingly strong requirements in terms of productivity, flexibility, responsiveness and traceability. It is becoming increasingly difficult to meet these requirements using conventional approaches for workshop control. These latters combine prioritization and forecasting. A workshop control approach which marks a clear break from these conventional approaches

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P. Pujo · F. Ounnar (✉) · T. Remous
Aix-Marseille University, Av. Esc. Normandie Niémen,
13397 Marseille cedex 20 Marseille, France
e-mail: fouzia.ounnar@univ-amu.fr

P. Pujo
e-mail: patrick.pujo@univ-amu.fr

T. Remous
e-mail: tarik.remous@etu.univ-amu.fr

P. Pujo · F. Ounnar
Centre de Recherche sur le Transport et la LOGistique (CRET-LOG),
Marseille, France

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is proposed. Based on a combination of different emerging ideas such as holonic paradigm, internet of things, infotronics technologies, this approach is meant to be without hierarchical decision and without forecasting optimization.

To understand the scientific motivations of this control approach, firstly we present the evolution of the constraints faced by production systems, and therefore the constraints that must be considered by their control system.

The implementation of infotronics technologies in Wireless Sensor Network is presented. The extension of this implementation to the field of manufacturing, to create Wireless Holons Network (WHN) is discussed. It is highlighted that the PROSIS model and more generally, the isoarchy concept are in fact perfectly suited to serves as a formal framework to this control approach.

A first experiment, using WiSMotes (WSN from Arago Systems), on intralogistics system in a Holonic Manufacturing System is presented.

2 Motivations and Stakes

Faced with the rise of highly competitive country, the Western manufacturing world must adapt and create new business opportunities and profitability. This evolution of manufacturing systems is already expressed in the industrial world in different forms. For example, mass customization requires a flexible and individual product tracking. Another example, the lean approach, leads to a drastic reduction in inventories and improved flow control. We also find Six Sigma approaches, which bring more rigour and requirements in the result to be achieved, and finally the requirement traceability of the product, especially for the needs of security and maintenance. It is therefore necessary to gain in productivity and robustness in the context of variable production quantity, but still excellent in terms of quality, cost and time. All this appears as means to enhance the performance of production systems, both in terms of performance and in terms of quality of service. In fact, these evolutions are generated by those of the industrial production's context, corresponding to a greater variability in the markets or the need for customer satisfaction. They induce operation of production systems in search of higher productivity, thanks to the technological evolution of process, automation implementation, flexibility of operation and more recently, of their agility. Indeed, the product's life cycle gets shorter and their variants increase. These new production characteristics require reviewing mass production strategies. In fact, the production is currently considered around the production of small quantities in a family of parts with many variants, while reducing the Work In Progress (WIP). For this, the production system must be more flexible, i.e. it must be able to easily manage diverse and variable productions. This translates into more disturbed, less predictable production systems, responding to an obligation of product flexibility, of flexibility in capacity, of responsiveness and adaptability.

The current challenge in industrial engineering is to develop control production systems that can support these different aspects.

To achieve these objectives, new control approaches must be found on the basis of firstly breaking with the pure forecasting control approach and secondly, on better taking into account of real state of production system. These control approaches will allow implementing more efficient and robust real time decision-making mechanisms.

In order to be more responsive and effective in a more disturbed environment, the production must be controlled closer to the real progress of tasks. Since it is necessary to have more and more information collected in real time, the concept of *communicating product* able to generate a lot of information throughout the production cycle appears to be an appropriate solution. This alone is not enough. Indeed, entirely or partially centralized methods used for decision making during the workshop control have significant limitations in relation to the increase of the data volume and to the reduction of the reaction time. Therefore it impacts the processing: required time calculation too great, forecasting methods unsuited to the needs of variability, difficult instrumentation of the state of the workshop, in particular if it is necessary to exploit the information with a centralized decision-making process…

It is therefore essential to explore new production systems control approaches, fully adapted to these new constraints. Among all possible solutions, control architecture without any hierarchical dimension in the decision making mechanisms and based on the use of infotroniques technologies is proposed here. Indeed, first, we consider that there is no hierarchy in the decision-making system given that, for the same decision level, all the entities have the same authority in the decision-making mechanism. This does not imply that there is no structural hierarchy. On the other hand, the infotroniques technologies, such as contactless identification, wireless communications and ambient computing, represent a considerable potential for transformation of the operation of production systems. The presented work is therefore aimed to explore new ways of improving the flexibility, security and performance of production systems by introducing these technologies at the heart of their control system and relying particularly on Wireless Sensor Network (WSN) technology.

3 Wireless Sensor Network Technologies for Holonic and Isoarchic Control

3.1 Wireless Sensor Network

Wireless Sensor Network (WSN) [1] consist of autonomous sensors called sensor node (or *mote*), for physical intended to collect physical or environmental data such as temperature, acceleration, pressure, etc. Once the data obtained, they are independently routed through a communications network through a multi-hop routing between motes, to a base node called sink node (or *sink*). Wireless sensor network is scalable, it consumes very little energy, is intelligent and programmable, is able to quickly collect data, is reliable and accurate in the long term, is inexpensive to purchase and install and requires very little maintenance [2]. WSN applications are numerous [3–5].

In the fields of security and military applications, we can cite monitoring of claims, deployment in strategic or difficult to access areas, distributed alarm systems for intrusion detection, monitoring in real-time of aircraft structures, ships, automobiles, subway, or the alteration of building structures, roads, docks, railroad, bridge or hydroelectric dams.

In the environment field, WSNs enable the detection of fires, pollution or meteorological events, seismic monitoring [6], the detection of toxic leaks (gas, chemicals, radioactive elements, a.o.) [7]. They allow the observation of biological systems, by the collection of information on the state of natural habitats and behaviours of the fauna and flora (displacement, activity, health).

There are also many applications in the field of Health and Wellness [8]: monitoring of vital functions of a living organism, transmission of data on the activity of a human body (undergone accelerations, glucose monitoring).

Industrial applications are also emerging: improving the storage and delivery process in the case of a cold chain, optimizing of building systems for lighting, water supply, heating, air conditioning, etc.

3.2 Holonic and Isoarchic Control: The PROSIS Model

In the Holonic Manufacturing Systems (HMS) community, where the holonic paradigm [9] applied to the industrial world has been studied, it is recognized that the holons are autonomous, cooperative and recursive belonging to one of three types of basic holons, namely Product, Resource and Order Holon [10].

The Product, Resource, Order and Simulation Isoarchic System (PROSIS) model [11] follows on from this work, by focusing on the holonic approach around an isoarchic decisional architecture, removing all forms of hierarchy between holons. The term ‘isoarchy’ comes from the combination of the Greek prefix ‘iso’(equal) and the Greek suffix ‘Archy’ (power). The isoarchy is a control approach where the holons involved in a decision contribute to the development of this decision with an egalitarian manner. They must do so with a maximum of skills and knowledge about their states. For this, the decision-making architecture and the information system should be as close as possible to the material organization of the production system.

A holon is composed of a physical part, called M_holon, and an information part, called I_holon, bringing to the holons its decisional intelligence. For all holons whose M_holon are mobile, the I_holon can be implemented in a WSN mote fixed on the M_holon. The integrity of the information and decision-making system regarding the material state of the production system is obtained by fixing a WSN mote on the material part (M_holon) of each holon. This WSN mote constitutes its informational and decisional part (the I_holon). For holons whose

M_holon is static (mainly, WorkStation Holons), the I_holon is implemented in a computer called Ambient Control Entity (ACE) used as a sink for WSN motes and located locally near him.

3.3 Use of Wireless Sensor Network in a HMS

Figure 1 shows the architecture of a mobile holon, which integrates a WSN mote as I_holon. This concerns each Product Holon and each Order Holon, but it also relates to the mobile Resource Holons such as shuttles. The identifier given to each mote corresponds to the identification of the associated I_holon.

Figure 2 shows the relationship between an ACE, a WorkStation Holon, a sink, and all ambient services provided by the ACE to other Holons.

Direct communication between ACEs via a wired network of Ethernet type allows connecting different parts of the WSN, in the case where some motes are sufficiently distant to interrupt the communication between them and the rest of WSN. In addition, each ACE ensures Graphical Interface with the human workstation operator.

Finally, the HMS is composed of holarchy of motes (PH, RH, and OH) and EPAs (RH) located at the same decision level. The I_holon (mote) supports state data and other information of the holon. It can access the ambient services provided by ACEs, available in open access and configured according to the expressed needs. These services allow each holon to take decisions and to interact with other holons having an equivalent level of decision. This may involve complex issues, such as finding an optimal path for a shuttle, choosing a product to be processed on a resource, and taking into account multicriteria analysis for the establishment of a compromise or evaluating a future performance.

Fig. 1 Internal architecture of a mobile holon

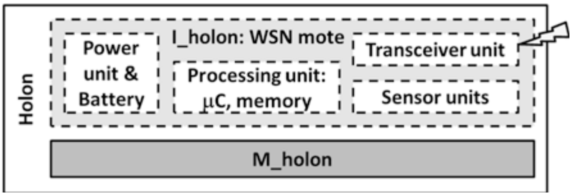
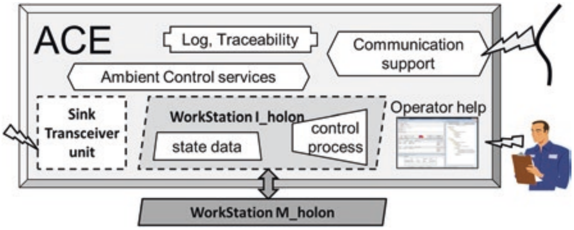


Fig. 2 Internal architecture of a workstation holon in an ACE



For example, the invocation of a multicriteria decision support service requires to specify the configuration of the decision model, the configuration of the access mode to necessary information (some of these information are related to real time considerations), and the identification of the concerned holarchy. For that, the ACEs, services provider, contribute to the development of an ambient intelligence system addressing a set of communicating and intelligent entities: Holons. The set, ACEs and motes, constitutes a Wireless Holons Network.

4 Case Study: Intralogistics Control in a Job Shop

The cooperation between holons allowing the emergence of the job shop control solution will not be described here: the used mechanisms are similar to those described in [12 and 13]. We focus on the interconnection between production activities, i.e. the tasks to be performed, and the intralogistics service between workstations. The functions allowing the control of this intralogistics service will be presented.

4.1 Intralogistics Control

There exists in our university a production factory designed to be flexible and to produce small manufactured objects. This test bed allows us to validate our models related to an isoarchic and holonic control and to show that they can be implemented with the current technology level.

Currently, textile products are manufactured in the production factory. Each workstation (with human operators) includes a computer and a machine such as: sewing machine, overlock machine, ironing board, electric scissors, a.o.

The intralogistics is ensured by a Montrac transport system (www.montratec.com—Schmid Group). The Montrac system is composed of monorail shuttles and of a flexible railroad network composed of rails, curves and divert points. It is easy to estimate the transportation times as the shuttles have a constant speed and the routing is static (a shuttle always has the same trajectory between two points). The M_shuttles cannot communicate when travelling, but interaction with them is possible on each workstation via an infrared serial port (IRM—Intelligent Routing Module).

A first version of shuttles' control, integrated in the developed HMES (Holonic Manufacturing Execution System) using the PROSIS principles was presented in [14]. We present here the progress offered by the WSN technology.

4.2 Arago Systems—WSN Technology

Arago Systems' WiSMote (www.aragosystems.com) is an open platform designed for R&D in Wireless Sensor Networks (WSN). It is based on a 16-bit RISC architecture (TI MSP430 5-series) and an IEEE 802.15.4 transceiver (CC2520) DSSS compliant baseband modem providing 250 Kbps data rate and targeting 2.4 GHz ISM band applications. It is provided with a Unique Serial ID and an external serial Flash memory for data logging. Three sensors are available on the board: temperature, luminosity and 3-axis accelerometer. WiSMote embeds Contiki, a small footprint, highly portable, multitasking Operating System which supports IPv6 (6LowPAN) protocol. Programming is done in C language and supports multithread applications.

4.3 Shuttle Holon's Control

In [14] two essential mechanisms for the control of the shuttle Holon's tasks are presented: the allocation of transport tasks to a given shuttle via a Call for Proposal service, and the ranking of these tasks via a multicriteria analysis taking into account the distance to the destination, the priority of the product and the required arrival time. WSN technology allows to better control the behaviour of the shuttles and to make the state variables of the corresponding holons robust. This can be illustrated by the Discrete EVent System (DEVS [15] model of management of shuttle's states, see Fig. 3). A shuttle can be free pending or free but moving to a Start Transport position. Then it joins a Target Transport position being loaded. So, a shuttle can have or not a mission, it can be in motion or not, it can be loaded or not, etc. The transitions between these states are achieved based on internal information, embedded sensors information or external information (due to the reception of Wireless Messages (WM) coming from other motes). Any change of state involves traceability recording in order to calculate performance indicators.

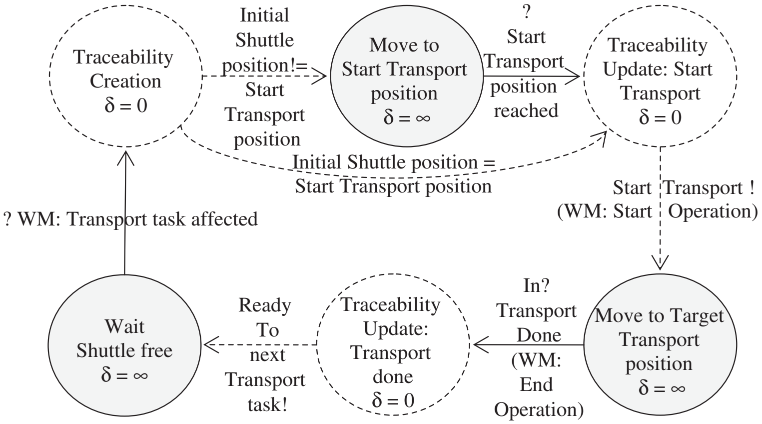


Fig. 3 DEVS state management model of I_shuttle

```
PROCESS(state_machine,"State_Machine");
AUTOSTART_PROCESSES(&state_machine);
static enum _stateMachine
{       state_Shuttle_free = 0, state_Move2Start, state_Move2Target
} stateMachine = state_Shuttle_free;
PROCESS_THREAD(state_machine, ev, data)
{       PROCESS_BEGIN();
        while(1)
        {PROCESS_WAIT_EVENT();
        switch(stateMachine)
        {       case state_Shuttle_free:
                        if(state_Shuttle_free_Output_conditions == TRUE)
                        {// Traceability Creation
                                stateMachine = state_Move2Start;
                        } else stateMachine = state_Shuttle_free;
                break;
                case state_Move2Start:
                        if(state_Move2Start_Output_conditions == TRUE)
                        {// Traceability Update: Start Transport
                         // Send Wireless Message to M_shuttle: Movement to Start WS
                                stateMachine = state_Move2Target;
                        } else stateMachine = state_Move2Start;
                break;
                case state_Move2Target:
                        if(state_Move2Target_Output_conditions == TRUE)
                        {// Traceability Update: Transport done
                         // Send Wireless Message to M_shuttle: Movement to Target WS
                                stateMachine = state_ Shuttle_free;
                        } else stateMachine = state_Move2Target;
                break;
        }}
        PROCESS_END();
}
```

Fig. 4 I_shuttle state manager's thread

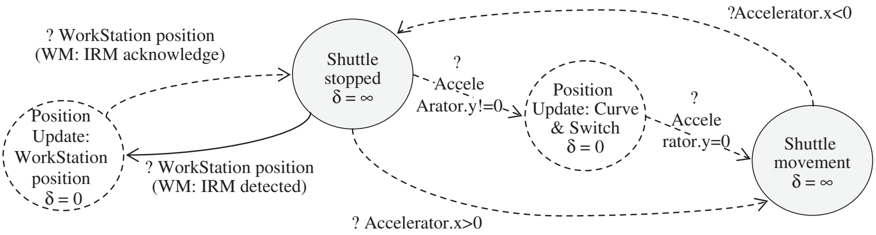


Fig. 5 DEVS movement state management model of I_shuttle

Each state graph is implemented in the mote in the form of a thread based on the principle given in Fig. 4.

Another example is related to a precise detection of the actually movements performed by shuttles. Indeed, the Montrac shuttle's control cannot indicates what happens between two IRM. However, the shuttle can be blocked by an unknown obstacle: another stopped shuttle or breakdown. Figure 5 shows the DEVS model of the shuttle movements' viewer. Thanks to the 3D embedded accelerometer on the mote, it is possible to detect motion and stopped states, the crossing of curves and diverting points. It is thus possible to manage the shuttle's states throughout its trajectory in a precise manner. During stops, it is possible to check if it is a stop before a WorkStation: the IRM of the WorkStation can communicate with the M_shuttle.

Otherwise, it means that the stop is abnormal, and a search procedure can be initiated: is there another shuttle stopped in the same place, and if so, can it restart?

5 Conclusion

An isoarchic control system of production systems was presented. It is based on a holonic paradigm, on decision-making mechanisms without hierarchical or forecasting dimension, and on WSN technologies for implementation. This proposed control constitutes a Wireless Holons Network (WHN). The interconnection between production activities and the intralogistics service between workstations was presented. The performed tests on our test bed show that the use of WSN brings new opportunities of flexibility, security and performance for production systems. We will continue the exploitation and the implementation of the WSN to develop the call for proposals service and to exploit the detection of the movements performed by shuttles. The cooperation between Holons allowing the emergence of the production system control solution will also be studied. A validation by simulation of the proposed solutions will be carried out by using the Cooja simulator [16]. This simulator allows the emulation of different motes. Indeed, the computer programs can be uploaded on the simulated sensors of the motes and the network connections between WHN motes (I_holons) can be also simulated.

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From Centralized Modelling to Distributed Design in Risk Assessment and Industrial Safety: Survey and Proposition

Nassima Aissani and Islam Hadj Mohamed Guetarni

Abstract Safety is seen as a key factor for successful business and an inherent element of business performance. As a result, industrial safety performance has progressively and measurably improved in terms of reduction of reportable accidents at work, occupational diseases, environmental incidents and accident-related production losses. It is expected that an "incident elimination" and "learning from failures" culture will develop where safety is embedded in design, maintenance, operation at all levels in enterprises. Today's safety analyses and proofs for certification purposes are still performed predominantly manual. However, the quantitative analysis, by its complex nature, introduced automation in the management of risk and industrial safety: statistics analysis, Bayesian methods and Bayesian networks. In this paper, a state of the art of computing in risk assessment and industrial safety will be presented: static, dynamic, centralized and distributed applications. Then, a proposal will be made to design a "Dynamic safety system" which aims at detecting and evaluating risks, then establishing prevention actions.

Keywords Decision making · Industrial safety · Risk assessment · Distributed modelling · Distributed control

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N. Aissani (✉) · I.H.M. Guetarni
Institut de Maintenance et de Sécurité Industrielle, Université d'Oran,
BP 1524, EL M'Naouer, Es Senia, 31000 Oran, Algeria
e-mail: aissani.nassima@yahoo.com

I.H.M. Guetarni
e-mail: hadj-islam27@hotmail.fr

N. Aissani
Laboratoire d'informatique d'Oran "LIO", Université d'Oran,
BP 1524, EL M'Naouer, Es Senia, 31000 Oran, Algeria

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1 Introduction

Safety is seen as a key factor for successful business and an inherent element of business performance. Initially, industrial safety paradigm was defined to propose and develop policy as a guide to assist employers and employees in complying with standards to preserve human life, the environment and equipment from hazardous and eventually fatal things that they may contract in the industrial workplace. Then, industrial safety evolved to define safety indicators, i.e. changing production parameters to be within a safety interval; then it became an important factor in the manufacturing control decision making.

Since the automation of industrial systems for control, security is seen automated also:

- First, automated risk analysis: statistical and probabilities analysis.
- Second, analysis by simulation for critical industrial process.
- Third, development of decision-support systems for safety: identification of risk and defining actions for critical situations.
- Forth, use of Multi-agents paradigms.

In this paper we will track the evolution of security and risk management, and show also the evolution of tools and their application areas. We will address also a modelling technique to design an effective decisional support system for safety in critical industrial systems.

The paper is organized as follow; first we will try to present a survey about computing in risk assessment and industrial safety showing the development of this discipline, “Industrial Security”, and lack of research using past events in automated dynamic decision-making processes. Then, we will present the interest of using distributed modelling techniques in many manufacturing problem resolution. Next, we introduce an accurate multi-agent model that has already been used in previous studies, but with some modifications to deal with safety context. Finally, our conclusions are presented, summarizing the use of automated techniques in risk assessment. Finally our contributions and perspectives for future research are described.

2 Computing in Industrial Safety and Risk Assessment: State of the Art

Understanding risk and having the right strategies in place when an incident occurs is becoming more evident and essential. More and more, organizations are faced with the need to measure and reduce their risks. Many Quantitative Risk Assessment methods appear. With the culmination of methods of risk analysis, the indispensability of using computers became evident [1–4].

2.1 *Statistical and Probabilities Analysis*

At the beginning, statistics was used in order to save intelligent and organized data related to equipment history, production systems and especially their problems and accidents information [5]. This formalization data enable decision makers to improve their policies in terms of protection of employees, environment and equipment. Statistics was widely used for risk assessment in many fields (for this first section we consider a number of fields analysing the presence of risks).

Finances is definitely the first area where statistical analysis was used to estimate risks. Blume [6] underlines the importance of integrating risk measurement in financial analyses. He analysed the coefficient of non-diversifiable risk or the beta coefficient in the market model. Galindo and Tamayo [7] made a comparative analysis of different statistical and machine learning modelling methods of classification on a mortgage loan data set with the motivation to understand their limitations and potential. They suggested also the use of accurate predictive models, such as the standard Probit algorithm, as ingredients of institutional and global risk models.

Industry is our concern; statistics for industry and technological risk assessment is widely studied. Slovic et al. [8] stressed that extensive statistical data is readily available at that time—for example, the frequency and severity of motor vehicle accidents, being well documented at that time. Paté-Cornell [9] described deterministic and probabilistic methods of treatment of risk and uncertainties, and the different viewpoints that shape these analyses. Six different levels of treatment of uncertainty are presented and discussed in the light of the evolution of the risk management philosophy in the US. Currently research works are done to make an extensive data analysis for risk assessment, for example Hu et al. [10] proposed the Formal Safety Assessment (FSA) concept which is a structured and systematic methodology aiming at enhancing maritime safety. Authors discuss frequency and severity criteria in ship navigation. Bayesian approach is also widely used in risk assessment and industrial safety. In [11] the adequacy of Bayesian networks to integrated risk analysis models, is demonstrated by applying them to an industrial case that is a sub-set of an EDF energy power plant (a heat sink). dos Santos et al. [12] proposed the use of a Bayesian method called dynamic Markov blanket classifier that has as main goal the induction of accurate Bayesian classifiers having dependable probability estimates and revealing actual relationships among the most relevant variables.

2.2 *Simulation for Industrial Safety and Risk Assessment*

Simulation was used very early for risk assessment. In 1988 [13] studied the advantages of using simulation giving an adequate account of dynamic processes interacting with systems' states, which is what an operator is in reality confronted with. A more large overview can be find in [14]. So many simulation techniques are used for risk assessment, for example **Monte Carlo**: simulation performs risk analysis by building models of possible results by substituting a range of values (a probability distribution) for any factor that has inherent uncertainty. Hauptmanns [15] addressed a BLEVE (boiling liquid expanding explosions) problem in petroleum industry. Simulation is used for calculating missile trajectories and impact energies. **Petri-net simulation**: Labeau et al. [16] used Petri-net network to simulate a transient behaviour in a tank, corresponding to its pressurization. Pinna et al. [17] used a high level of Petri-net ("coloured Petri-net") for both: deterministic verification of safety properties and for the probabilistic assessment of reliability, availability or maintainability indicators. This simulation is a powerful aid to design decision support systems to assist the operator in the control of hazardous processes.

2.3 Decisional Support System for Safety and Risk Assessment

Using statistical data and simulation, many works are done to conceive decisional support systems for risk assessment and management. They are specially used for: fault detection, storage and classification of accident information and finally for making decision in emergency situations.

Fault detection in automatic safety is a key paradigm, so fault detection is important to identify risk situations. Rajakarunakaran et al. [18] developed a decision support system for safety management of rotary system using computational intelligent techniques. This system is based on Neural Network approach for fault detection and fuzzy logic approach for fault diagnosis.

Storage and classification GIRGIN [19] proposed an integrated decisional support system to list all the major industrial accidents that had taken place in Turkey and to define which accidents should be listed and in which known databases. This history or Return of EXperience (REX) can be used for making decision in critical and emergency situations.

Making decision for safety The idea of using decision support systems for safety is not new. [20] pointed the importance of using Decisional Support Systems (DDS) for disaster management, considering a DDS as one well organized database which can be interrogated in different manners and which can give a suitable answer establishing a safety policy in toxic spill management. Then, several applications have been developed in three main axes:

(a) *Making prevention policy*: In environment protection, there are many works about development of DDS for waste management; an extended review is given in [21].

(b) *Risk evaluation*: It is another way to use DDS to determine dynamically the risk of a considered situation, e.g. evaluating risks caused by the transport on road of hazardous material, considering weather, driver, stat of the road [22]. It is also used in environment prevention, for example to evaluate risk of groundwater pollution due to the use of pesticides in agriculture [23]. To do this characteristics of the aquifer are inserted in the geocoded database. Afterwards, the system assigns an intrinsic vulnerability value to each element of the grid. Then the system evaluates the degree of hazard by using different factors identified during the knowledge acquisition phase (such as the type of pesticide with particular reference to its physical chemical characteristics).

(c) *Reponses in crisis*: DDS are also used to suggest actions to perform in crisis situations. Turoff et al. [24] defines 8 principles to be considered in designing a DDS: Dynamic Emergency Response Management Information System, among them being: (i) the system directory should provide a hierarchical structure for all the data and information currently in the system; (ii) update Information and Data. DDS are used in the transportation of hazardous material, dealing with emergency, evaluating risk and proposing alternatives. Most of these applications are based on important knowledge bases and multi-criteria reasoning. Often, the duration of knowledge base consultation and the development of the response are important. Another type of interesting reasoning is *distributed reasoning* which can be executed by Multi Agent Systems (MAS).

2.4 Multi-agent Systems for Safety and Risk Assessment

MASs are suitable for complex system design, especially with different kind of parameters and constraints. Such systems are used for environment protection, simulation, risk evaluation and plan determination for emergency.

(a) *Environment protection*: An exhaustive state of the art was described by Aulinas et al. [25] showing the interest of researchers in using MAS for simulation, analysis and decision making in environmental issues. iForestFire (Intelligent Forest Fire Monitoring System) is an interesting application of the use a *Holonic*[1] approach (which we consider here as a particular case of agents) for forest fire management and early detection [26].

(b) *Simulation and risk evaluation*: MAS can be used in continuous self-learning and evolution algorithms for risk identification, starting from risk factor groups to determine the right risk identifier by stabilizing the average concentration [27]. Multi-agent dynamic risk modelling (MADRM) is also used in safety assessments of a runway incursion scenario [28]. It is based

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[1] Holons are autonomous and cooperative entities representing manufacturing component and activities (products, resources, orders) according to Arthur Koestler.

on four types of agents: the aircraft taking-off and taxiing, the pilots flying the aircraft, the runway controller and the ATC system. Compared to Event sequence analysis (MADRM) is more efficient, for example. The risk reduction by the ATC alert system was assessed to be a factor 19 by the event tree-based approach versus only a factor 1.06 by the MA-DRM-based approach.

(c) *Emergency management*: MAS are used to simulate and predict behaviour in crisis situations or to develop a DDS. In [29] a multi-agent organization of a decision support system for flood emergency management is described. It was tested on two different river basins in Spain; the developed DDS provided enough flexibility and efficiency to operate on real time. WIPER [30] is an interesting application about the use of heterogeneous networks to detect possible emergencies, as well as to suggest and evaluate possible courses of action to deal with the emergency. WIPER uses dynamic data from cell phones and analyses the data in real time. Mobile Agents are used to anonymise and pre-process the data stream at the cellular service provider. For the Detection and Alert System, it is advantageous to build data mining and anomaly detection agents, which can be migrated directly to the cell phone providers. This would allow the data to be analysed at the source, reducing the overall network traffic and improving performance. Some researchers studied emotional behaviour in crisis situation using agents. Emotions play an important role in disaster management. Kefalas et al. [31] developed a formal model for agents demonstrating emotional behaviour in emergency evacuation, taking into account emotions structures, personality traits and emotion contagion models. Experiments were conducted to demonstrate the feasibility of the model refinement and to obtain an initial insight on how emotions and emotion contagion can affect evacuation times. The use of Learning in multi-agent architecture is also proposed for risk management [32] to take decision when data lacks. In this section, it could be seen that distributed organization is widely used in safety and risk management this last decades, and especially the multi-agent paradigm.

3 Dynamic Control and Distribution

Multi-Agent System (MAS) are independent, being able to receive information from their environment, act on that information and generally behave in a rational manner. We have experimented this approach to control job shop scheduling and scheduling production and maintenance tasks in the petroleum industry [33] and also in multi-site control [34]. Holonic approach is also used by our team [35–37]. The holonic paradigm is explicitly created for complex environments with automated parts, mixing information and physical components. Holonic concepts such as autonomy, cooperation, recursiveness and reconfigurability are important features to meet the requirements imposed by current industrial systems. The reactivity was often a motivation for the use of distributed architectures. Reactivity is the capacity of a safety system, to respond to crises, because the response must be quick and in near real time. As seen in last section, distributed paradigm, in general, are still limited when centralized decision-making process makes the system vulnerable.

In the next section, the architecture of a dynamic safety system using agents will be suggested before describing its implementation.

4 The Proposed Approach Organization

Aiming at improving the effectiveness and accuracy of safety management, the proposed integrated safety dynamic system analyses how subsystems, components, humans and environment interact based on the system's interfaces, the knowledge of system and process function, historical database and monitor the system.

This safety dynamic system (Fig. 1) receives data from the industrial system—real time monitoring data, and from an expert knowledge base the prognosis about risk evaluation and actions to perform (e.g. change of the maintenance plan). These data are used in risk evaluation and fiability prediction. A multi-agent system is then proposed to calculate new safety boundaries about resources and elaborate maintenance plans, which may impose new constraints for the industrial system.

4.1 Multi-agent Framework for Industrial Safety

In this section, the multi-agent system architecture is presented. This system was already used to control a job-shop and to resolve a scheduling problem [33] and in this paper, it will be adapted to safety goals . We start by presenting the agents then their interactions.

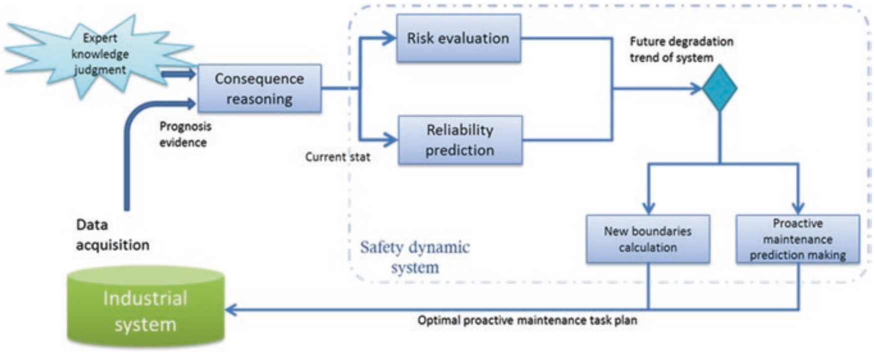

Fig. 1 Safety dynamic system architecture and its interactions

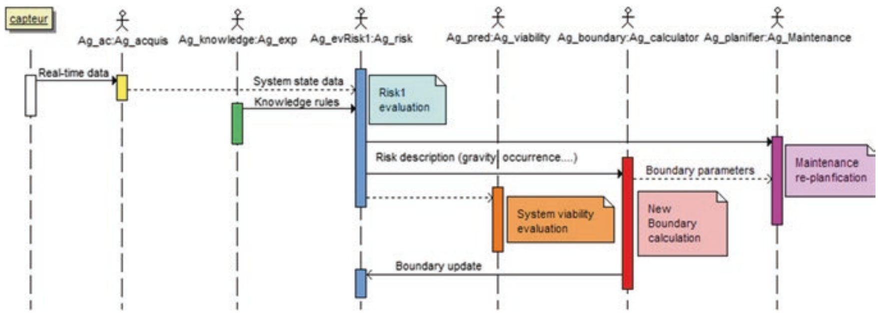

Fig. 2 UML sequence diagram: interactions between agents

4.2 Multi-agent System Organization

Six types of agents are suggested for the Safety dynamic system presented in this paper (Fig. 2):

- Agent_Acquisition (Ag_acquis): the nearest agent of the industrial system, receives data from sensors and codes them for later treatment.
- Agent_Knowledge (Ag_exp): this agent summarizes the expert knowledge in a knowledge data base and, according to observed data, it sends adequate expert judgments.
- Agent_evaluate_Risk (Ag_risk_i): each agent of this type is dedicated to a specific risk. Using data received from Agent_ Acquisition and suggested prediction or evaluation from Agent_Knowledge, it evaluates the risk: it is present or not and to what degree.
- Agent_viability (Ag_pred) it evaluates the system performances, predicting it's evolution in term of viability, and sends this information to the boundary calculator.
- Agent_Boundary (Ag_calculator) with the given risk evaluation, calculates new safety boundaries concerning resources and products, these new boundaries are sent to Ag_risk_i to re-evaluate risks and to Ag_Maintenance.
- Ag_Planifier (Ag_Maintenance) elaborate maintenance plan, according to regulations and safety boundaries that might be respected.

5 Conclusion

This paper is intended to be an introduction to distributed modelling in automated safety systems in industry. The path was drawn from the automation of static analysis in various fields, such as: finance, industry, environment, a.o. to the multi-agent risks modelling and analysis, and providing decisional support. The use of

MAS in safety has been of particular interest this last decade. At the end, a distributed dynamic safety system was proposed, based on multi-agent paradigm, as our contribution to the safety area. The implementation solution and experiments will be presented in another paper.

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A Multi-agent Based Platform for Safety Control

Brahim Boudiaf, Soraya Zebirate, Nassima Aissani
and Abdelkader Chaker

Abstract Safety becomes a key paradigm in industrial systems because of international regulation and the cost generated by a work stoppage or to overcome disaster. The work presented in the present paper describes a distributed modelling of a safety system for technological processes, and its application to permanent magnet DC-motor. Motors are basic engines in several technological systems and especially in industry their availability and security affect the entire system. For this purpose a special attention is paid to their supervision and security. The safety model is based on agents. These agents monitor system parameters, identify risk, trigger corresponding alarms and react to protect the system. Experiments have shown that the right alarms are triggered and the system reacts in near-real time to protect the equipment.

Keywords Safety control · Industrial safety · Multi-agent system · Permanent magnet DC motor

1 Introduction

Motors are basic engines in several technological systems and especially in industry, the motors' availability and security affect the entire system. Brushes in permanent magnet brushless dc motors have been developed in [1, 2]. For this purpose a special attention is paid to their supervision and security. Several works

S. Zebirate · N. Aissani (✉)
Institut de Maintenance et de Sécurité Industrielle, Université d'Oran,
BP 1524, EL M'Naouer, Es Senia, 31200 Oran, Algérie
e-mail: nassima.aissani@yahoo.fr

N. Aissani
Laboratoire d'informatique d'Oran "LIO", Université d'Oran, BP 1524,
EL M'Naouer, Es Senia, 31200 Oran, Algérie

B. Boudiaf · S. Zebirate · A. Chaker
Laboratoire SCAMRE, ENPO, BP 225, Bureau Zerbani Mohamed Es-Senia,
31106 Oran, Algérie

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have been proposed as Safety and Security Multi-agent Systems [3] and a new safety feedback design for multi-agent systems [4]. In this paper, Risks in motors are identified and a distributed safety model is developed based on a multi-agent system which monitors and detects risks on motors. Distributed systems unlike to centralized ones are used for their reactivity and ability to resolve complex problems. Monitored parameters and multi-level safety can be considered as complex system. The research described in this paper has been developed in this direction. A similar work is reported in [5].

The present paper is organized as follows: in the second section, risks in DC motors are presented. In the third section, distribution for safety will be proposed together with a literature survey which shows that distributed modelling of safety systems became a promising alternative in safety problems resolution. The fourth section describes the mathematical model of the DC-Motor based on standard assumptions and a distributed safety system model based on multi-agent in a static and dynamic presentation. The fifth and sixth sections are dedicated to the implementation and experimentation of this system. Finally, a conclusion summarizing the experimentation of distributed modelling in motors' safety is stated, offering new perspectives that can be verified in the future.

2 Risks in DC Motors

An electric motor is an electromechanical device that converts electrical energy to mechanical energy. DC motors are available in a wide range of sizes, but their use is generally restricted to a few low speeds, low-to-medium power applications (like machine tools and rolling mills) because of problems arising at mechanical commutation. Also, they are restricted for use only in clean, non-hazardous areas because of the risk of sparking at the brushes [6].

Industrial motors frequently operate under varying load conditions due to process requirements. A common practice in this situation is to select a motor based on the highest anticipated load; this induces the perspective of permanent motor underloading. The biggest risk is overheating of the motor, which adversely affects the motor's life and efficiency, and increases operating costs. Voltage unbalance can be even more detrimental to motor performance and occurs when the voltages in the three phases of a three-phase motor are not equal. This is usually caused by the supply of different voltages to each of the three phases. It can also result from the use of different cable sizes in the distribution system. That is why an effective control system must guarantee the quality of product, but also saving energy without neglecting the safety of personnel and facilities. Risk management of any industrial process induces organization of hierarchical control systems in three levels of intervention:

- *Level 1*: provides continuous or discontinuous process control in normal operation.
- *Level 2*: provides a protection process based on predefined information about exceeding critical thresholds.
- *Level 3*: is the highest security in case of failure of one or more elements of the process.

3 Distributed Modelling for Safety

The greatest advantage of distributed modelling is the ability to overcome the "loss" of information due to spatial and temporal averaging. In distributed modelling the system's size is easily controlled by adding or removing components or entities, preserving system reliability (e.g. redundancy can be easily supported) which means robustness and also being reactive, because each entity is autonomous in taking decision without considering any other entity if that one does not need. In the last decades distribution became an alternative to centralized and static safety control systems [7]. Multi-agent systems were mainly used for two kinds of safety problems: first, system diagnosis and risk identification and evaluation; secondly, system recovery and prevention.

The multi-agent dynamic risk model (MA-DRM) has been developed by Stroeve et al. [8] which is based on assessment or the runway incursion scenario; agents are used as alert detectors. This model can be used in applications for technical risk identification.

Often, risk identifying applications are completed by a process which develops action plans in case of emergency. Multi-agent systems have been used by Panasetsky and Voropai [9] to identify risks in electrical network; such a MAS provides reactive power control by coordinating the work of different discrete and continuous control devices in a post-disturbance period. The existing state of the art in the field has encouraged us to use a multi-agent system for dynamic management of risks related to a DC motor. In the next section we will detail the motor's model and the architecture of the distributed safety system.

4 Safety Control System Architecture

Safety control system architectures help reducing the risks associated with the operation and maintenance of electrical equipment. They provide rugged process control for applications requiring a higher level of personnel protection. An example shows the simplest thing we can do with multi-agent system to control permanent magnet DC motor system model. The structure of the DC motor shown in Fig. 1 is a simplified version of the one used in industry.

4.1 The Model of the Motor

The model of the permanent magnet DC motor is shown in Fig. 1, where R is the armature resistance, L is the armature inductance, v is the voltage applied to the motor, i is the current through the motor, e is the back emf voltage, J is the moment of inertia of the load, B is the viscous friction coefficient, T is the torque generated by the motor, and ω is the angular position of the motor.

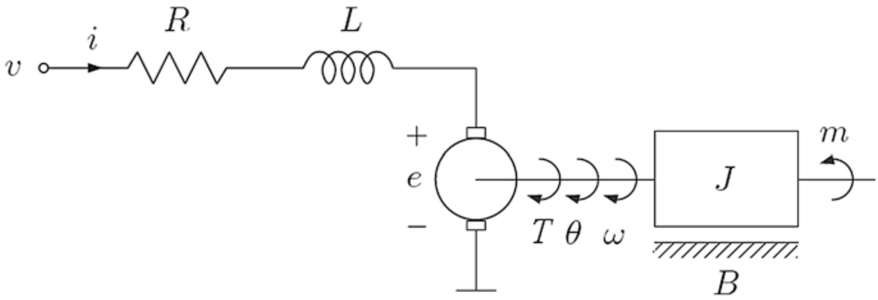

Fig. 1 Permanent magnet DC motor system model

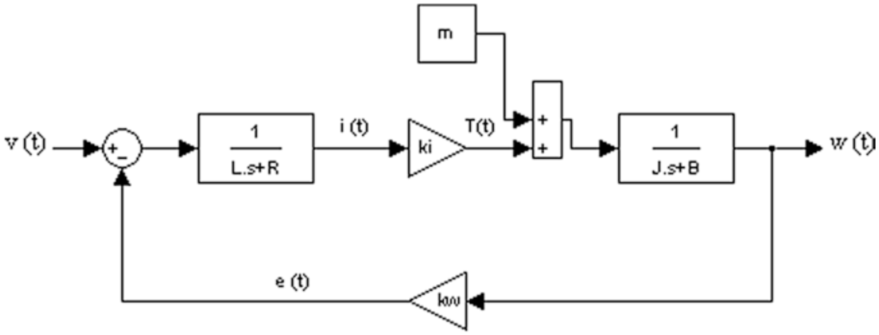

Fig. 2 Permanent magnet DC motor system Simulink block diagram

In SI units, the numerical values of k_ω (the back emf constant) and k_i (the torque constant) are the same [10]. A block diagram representation of the DC motor system is shown in Fig. 2. Thus, the transfer function from v to ω (by assuming m = 0) is:

$$\frac{\Omega(s)}{V(s)} = \frac{k_i}{(Ls + R)(Js + B) + k_\omega k_i} \tag{1}$$

where Ω(s) and V(s) are the Laplace transforms of ω(t) and v(t), respectively.

Using measurements obtained by the platform [10], the parameters of the DC motor system are: $R = 5.65\ \Omega$, $L = 2.90 \times 10^{-3}$ H, $B = 2.03 \times 10^{-5}$ Nms, $J = 1.88 \times 10^{-6}\ \mathrm{Nms}^2$, $k_\omega = 2.39 \times 10^{-2}$ Vs, $k_i = 2.39 \times 10^{-2}$ Nm/A.

4.2 *Distributed Safety Model Architecture*

The safety control system is linked to the system which is composed of the physical device (the DC motor) and its control part. The safety part is a group of agents that monitor the system, emit specific alarms and propose actions (Fig. 3). These two systems constitute a secure system. Each *Sensor agent* monitors one critical parameter of the system (e.g. temperature, speed, etc.), codifies this information

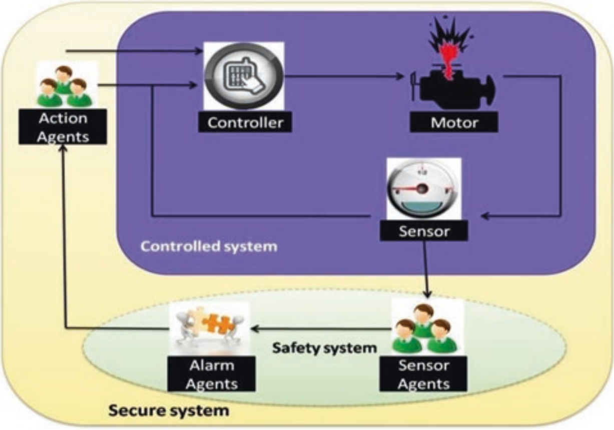

Fig. 3 Safety system architecture

and sends it to the group of *Level alarm agents*, which are classified according to security level (as mentioned in Sect. 2). Each agent perceives sensors' data and decides whether there is a risk or no and if its alarm should be triggered. All triggered alarms are sent to the main *Alarm agent* which analyses this alarm and determines the main risk that was at the origin of these alarms. Then, this information is sent to *Action agents* to activate a corrective action according to the received alarm and risk identification, using case based reasoning (Fig. 4).

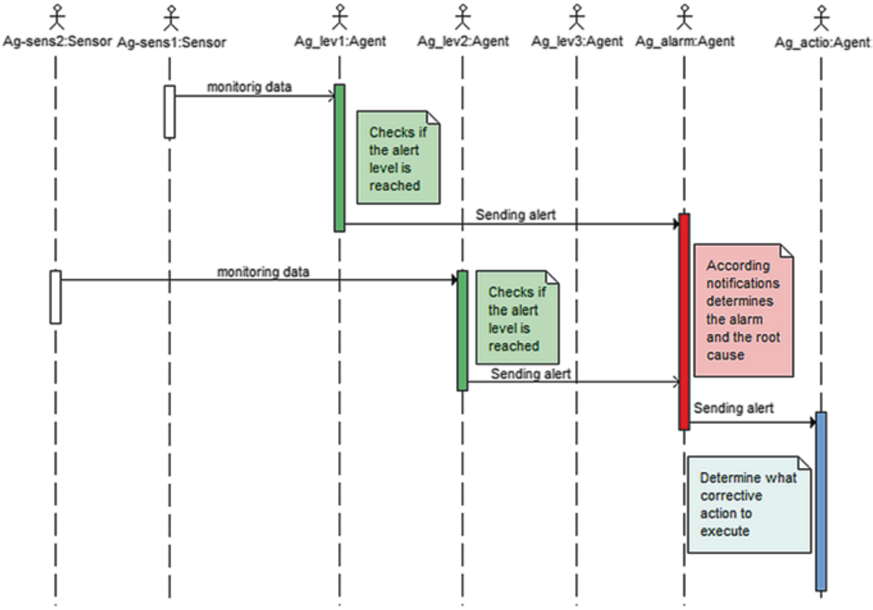

Fig. 4 Sequence diagram of agent's interaction

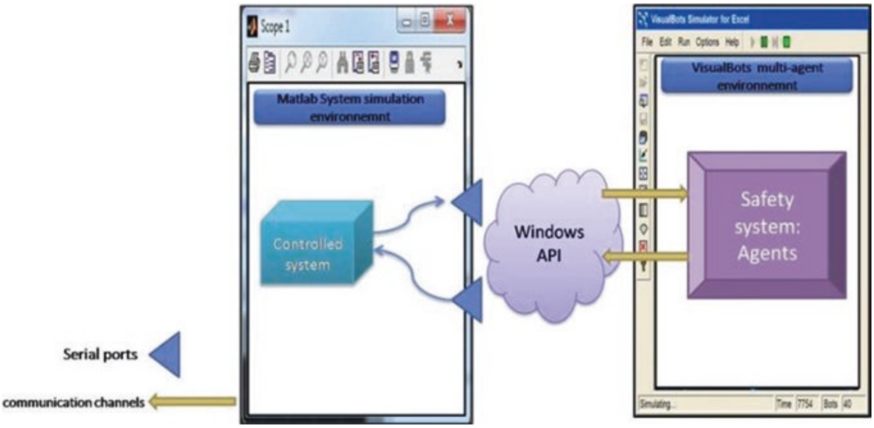

Fig. 5 The proposed secure system implementation

5 Safety Control System Implementation

For the implementation of this model "Visualbots" (http://www.visualbots.com) was used. Visualbots is a programmable ActiveX Control for Microsoft Excel using Microsoft Visual Basic for Applications that comes installed with Excel. We used Visualbots for its easy communication with Matlab which hosts the system simulation.

The safety system (agents implemented in Visualbots) uses serial ports [11] to communicate with the system (simulated on Matlab), see Fig. 5; these tow applications are developed on different support.

6 Experimentation and Analysis

The monitored system is a motor developed in Matlab/Simulink environment and according to the study done in Sect. 2, three main parameters are monitored: current, rotation speed and temperature. The data is sent via serial ports to the multi-agent system developed on VisualBots simulator which uses the Visual Basic language with interfaces in Microsoft Excel. The agent interface is developed in Excel to see triggered alarms and the affected security level. On this interface (Fig. 6) one can see the monitored parameters and their safety boundary; an alarm is triggered according to these informations (Fig. 6a). Then, a Level alarm agent triggers the level alarm (Fig. 6b) according to the information received from alarm agents.

The agents' reaction to perturbations in the system was studied in two experiments. Let's consider safety boundaries for this system: current 20 A and speed 7,000 rd/s.

ALARME 1

MAX 3

MIN 0

L'AGENT ALARME1 EST ACTIVER

ALARME 2

MAX 4

MIN 0

L'AGENT ALARME2 EST ACTIVER

ALARME 3

MAX 5

TEMPS 3

L'AGENT ALARME3 EST ACTIVER

Simulating... Time 30884 Bots 0

Fig. 6 Screen shot of safety system interface

First experiment: At time t = 0.1 s, a large step change in input voltage is introduced (Fig. 7a). So, a peak of current which attempts to go beyond 20 A (Fig. 7b) is noted, it's why an alarm is triggered. The safety system reacts and one can see that an action agent causes a power interruption, the agent signal goes from 1 to 0 and from 0 to 1 (Fig. 7d) which gives the current time to stabilize. In Fig. 7c, one can see the influence of the voltage perturbation on the motor speed; there is a jump from 4,000 to 7,000 rd/s, it doesn't go upper then 8,000 rd/s because of safety reaction of the system. To understand this reaction a second experiment is done.

Second experiment: To assess the robustness of the agent, we study the system from t = 0.4 s (Fig. 8a), so the motor speed tries to increase more than 7,000 rd/s

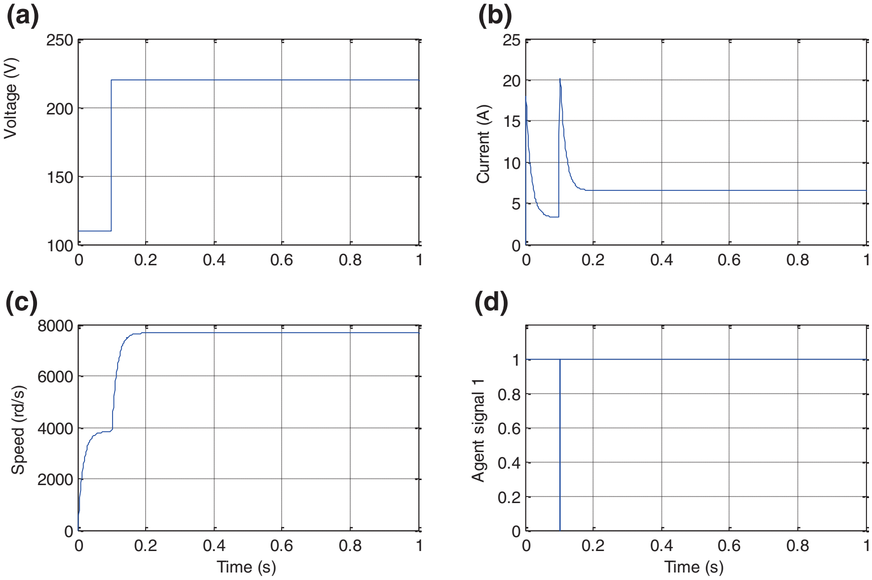

Fig. 7 Graphs for the first experiment

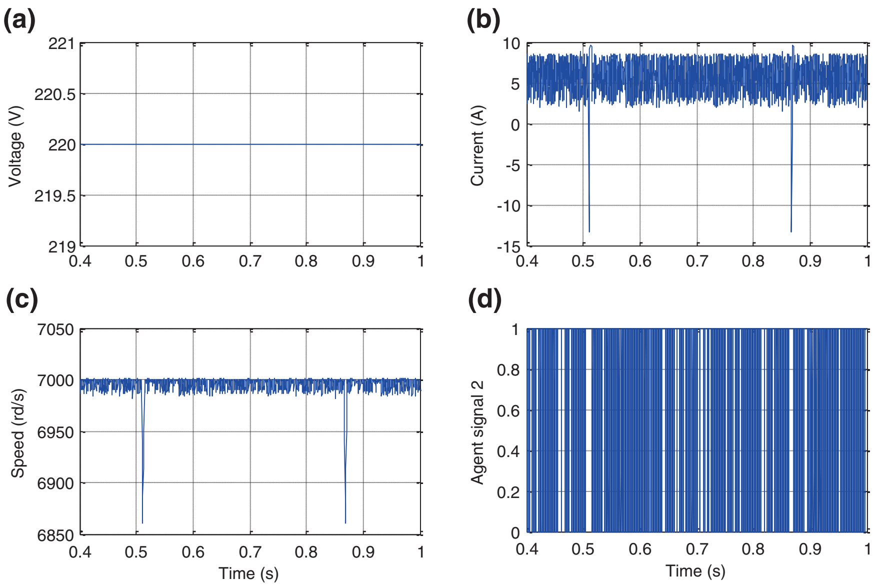

Fig. 8 Graphs for the second experiment

but it is stopped by the safety system, when the action agent causes successive power interruptions (Fig. 8d). The motor speed goes between 6,970 and 7,000 rd/s. The speed doesn't exceed 7,000 rd/s because of safety reaction of the system, except for situations of late response of the safety system (Fig. 8c). One can see in Fig. 8c that the current tries also to go between 3.5 A and 6.5 A. In Fig. 8b one can see that the current tries also to exceed 5 A but when power is shutdown, current signal goes down. At $t = 0.51$ s and $t = 0.87$ s, the current has changed to -14 A because of power interruption.

7 Conclusion

The work presented here is a solution for distributed modelling of safety systems for technological processes, applied to DC motors. The safety model is based on agents. Experiments have shown that the exact alarm is triggered and the system reacts in near-real time to protect the system. These two experiments open large perspectives taking into account more parameters and more complex systems. Another agent organization could be created, for example a hierarchy of sensor agents. Finally, experiments and system reaction could be interpreted to produce knowledge to improve in the future the system's efficiency.

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Part IV

Complexity, Big Data and Virtualization in Computing-oriented Manufacturing

Redundancy Mechanisms for Virtualized MES Workloads in Private Cloud

Octavian Morariu, Theodor Borangiu and Silviu Raileanu

Abstract Virtualization of manufacturing execution system (vMES) workloads offers a set of design and operational advantages to enterprises, the most visible being improved resource utilization and flexibility of the overall solution. This paper explores redundancy, as another important operational advantage introduced by the use of private clouds for MES virtualization. The paper briefly presents the main redundancy requirements for the workloads identified in ISA-95.03 based solutions and discusses in detail the strategies to assure redundancy of these workloads both individually and at solution level. A pilot implementation of these strategies using a private cloud system and CoBASA-type multi-agent MES architecture as examples is described and results are discussed.

Keywords Private cloud · Virtualization · Smart manufacturing · Redundancy · Fault tolerance · CoBASA · Event driven

1 Introduction

The migration from physical systems towards virtualization of software platforms gains more and more traction in modern enterprises across all business lines. There are a series of direct benefits offered by virtualization for almost any sort of software system: improved resource utilization, higher flexibility and availability, which help reduce operational costs for the enterprise. At the same time,

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O. Morariu (✉) · T. Borangiu · S. Raileanu
Department of Automation and Industrial Informatics, University Politehnica of Bucharest, 060042 Bucharest, Romania
e-mail: octavian.morariu@cimr.pub.ro

T. Borangiu
e-mail: theodor.borangiu@cimr.pub.ro

S. Raileanu
e-mail: silviu.raileanu@cimr.pub.ro

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virtualization is the main enabling technology for cloud computing in all delivery methods considered. Enterprises can take advantage of public cloud offerings to provision virtual workloads (IaaS), applications built for specific platforms (PaaS) or directly access in multi-tenant applications (SaaS) with convenient chargeback models, with no or minimal initial investment required. At the Manufacturing Execution System (MES) level, cloud computing adoption refers mainly to virtualization of MES workloads [1]. While MES implementations are different and usually depend directly on the actual physical shop floor layout, the general MES functions are aligned with the set of functions defined by ISA-95.03 specification. ISA-95 defines 5 levels for the hierarchical organization of a manufacturing enterprise, as follows:

- Levels 0, 1 and 2 represent the *process control* levels and their objective is to directly control the physical shop floor equipment in order to execute the actual production operations that result in one or more finished products;
- Level 3 is the *Manufacturing Execution System* (MES) level and consists of several activities that have to be executed in order to prepare, monitor and complete the production process executed at level 0, 1 and 2. The main activities at MES layer are: scheduling, quality management, maintenance, production tracking, and others depending on the specifics of each shop floor and manufacturing process. Several formal specifications and reference architectures for MES have been attempted [2];
- Level 4 is the *Enterprise Resource Planning* (ERP) level that executes the financial and logistic activities. These activities are not integrated in real time with the MES and the shop floor activities, and include: long term planning, marketing and sales, procurement, and so on. The dataflow at this layer is asynchronous and routed through an enterprise service bus.

This paper focuses on defining the **redundancy requirements** for each individual workload identified at Level 3 of ISA-95 specification and the redundancy mechanisms for the entire vMES solution. The study is done in the context of a virtualized MES (vMES) architecture with private cloud support and considers several scenarios where environment perturbations like *resource breakdown* and *rush orders* are interacting with the execution of the scheduled production.

2 Related Work

Cloud manufacturing (CMfg) represents an evolution of networked and service-oriented manufacturing models [3], with specific focus on the new opportunities in networked manufacturing (NM) enabled by the emergence of cloud computing platforms. While the concept itself refers to the most important issues related to cloud adoption, it does not cover the redundancy requirements specific to MES workloads. Other cloud based services for the manufacturing industry, like product design, product scheduling, batch planning, real time manufacturing control, testing, management, and all other stages of the product life cycle are described by Xu et al. [4]. Similarly, other research [5] focuses on typical characteristics of CMfg in relation to the key technologies and innovations implementing a CMfg service platform. Another important research direction is represented by the study of resource virtualization techniques and the resource sharing in manufacturing systems. Shi et al. [6] proposed a novel model for resource sharing in the context of grid manufacturing. This framework is composed of five layers: a network infrastructure layer, a manufacturing resource aggregation layer, a manufacturing resource management layer, a manufacturing service application layer and a portal layer. From a redundancy perspective, the resource aggregation layer introduced in this study can assure redundancy by reallocation of resources, if available. In a functional view on CMfg [4] the redundancy of the system is considered to be the sole responsibility of the cloud provider that assures fault tolerance at system level during the execution. IBM manufacturing integration framework handles redundancy by leveraging the clustering capabilities of the IBM middleware platform based on Tivoli product stack [7]. This paper goes beyond the above mentioned studies by discussing the specific redundancy requirements of each MES workload in both normal operation modes and in perturbed operating modes, specifically considering resource breakdown and rush order scenarios.

3 Redundancy in Virtualized vMES Based on ISA-95 Specification

In this chapter the redundancy requirements of the individual workloads of ISA-95.03 based systems are presented and discussed. At the same time the solution wide requirements for redundancy and a proposed approach are analysed in detail.

3.1 Redundancy at Individual Workload Level

ISA-95.03 specification defines a set of functions at MES level (Level 3). The most important functions are presented in Table 1, together with their corresponding redundancy requirements:

3.2 Redundancy at Integrated System Level

At the system level, redundancy mechanisms that would detect and correct a system failure must be implemented. This paper proposes a mechanism based on workload monitoring that is able to detect failures and unexpected events in real time and process them based on rules in order to assure smooth execution of the

Table 1 Redundancy requirements for vMES workloads

ISA-95 level 3 function	Redundancy requirements for vMES workloads
Production scheduling	Is responsible of algorithms and computation required to calculate the operation sequence for each batch product and shop floor resource allocation for each operation. Redundancy requirements for this workload can be achieved using an active/passive setup, with automatic fallback
Production execution	Drives the actual execution of the detailed production schedule on lower level systems. This workload is scaled horizontally and so redundancy is implicitly active/active with real time data replication
Production tracking	Tracks each product during the execution phases from the initial entry in the manufacturing process until completion. This workload is also scaled horizontally with active/active nodes and data replication
Resource management	Is responsible with the management of the shop floor resources in terms of availability, utilization, raw materials stocks, etc. An active/passive setup with a standby workload assures the redundancy
Automated control	Provides capabilities for automatic reconfiguration of the system, allowing the system to respond to unexpected events, like resource breakdown or rush orders. The workload is passive, and only activated when certain unexpected events are triggered
Historical data management	Assures traceability of all operations performed on every product. The complexity involved with this function depends largely on the nature of the products being manufactured and on the legal requirements that apply. Redundancy is assured at database level and depends directly on the RDBMS system chosen. Generally, the implementation consists in an active/active cluster with real time data replication
Quality assurance	Assures the product meets the acceptable quality criteria. This can be done by video inspection, x-ray scanning or by other specific means

manufacturing operations. The implementation of such a mechanism requires prior definition of the following items:

- *Workload Redundancy Profile*: a metadata document that describes the workload redundancy characteristics, as described in the previous section. Specifically, this profile contains: the test procedure to detect a failure (this can vary from executing a SQL command, a ping, a HTTP request, etc.), the clustering settings (active/active, active/passive), and the failure action (which dictates what needs to be done if a failure is detected).
- *Event Definitions*: a metadata document defining the possible events that may occur during the manufacturing process. Events can be Rush Orders, Resource Breakdown or specific workload failures.
- *Recovery Rules*: a document consisting of mappings between event definitions and possible actions in case of a failure.

The integrated redundancy mechanism introduced in this paper is presented in Fig. 1. The main components are:

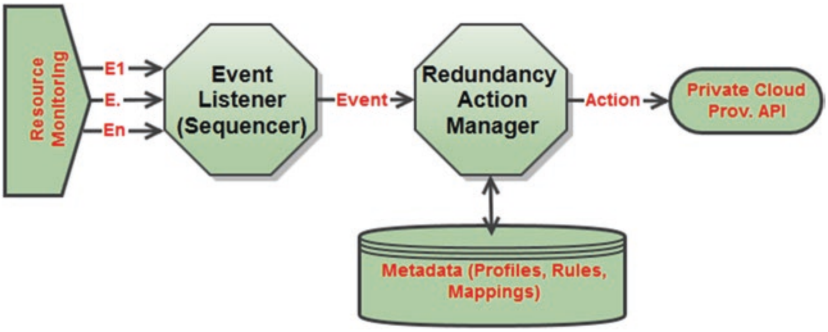

Fig. 1 Integrated redundancy mechanism

Resource Monitoring is responsible for actively monitoring the manufacturing resources and the workloads' execution. In practice, the resource monitoring component in a distributed multi agent system implementation can gather monitoring data from multiple layers in the enterprise software stack. For this reason, in case of a failure, multiple events can be generated by each monitored layer (database, middleware, protocol, workload, cloud, etc.). At the same time, business applications can also generate special events, specifically when Rush Orders must be handled.

Event Listener (Sequencer) is listening for generated events and sequences of these events. Because multiple events, distinct in regards to each other, can be generated for the same failure and at the same time, for efficient processing these events must be sequenced, and duplicates must be eliminated at the event listener module. This prevents overlapping actions being taken for the same root cause.

Redundancy Action Manager is the profile enforcement point for the redundancy mechanism. The profiles are evaluated based on the event mapping done by the system configuration engineers at design time. Then it parses and executes the failure action that typically calls the private cloud APIs to bring up a passive cluster node or to provision resources to the workload. Several specific scenarios for manufacturing enterprises are supported by the redundancy action module. The two scenarios considered in this paper are: resource breakdown and rush order handling.

The *resource breakdown* events are triggered when the resource controller detects that a resource cannot execute manufacturing operations as per the current schedule, for various reasons (hardware failure, controller failure, communication problems, etc.). The redundancy action manager differentiates between the possible failure types and triggers the corresponding failure action. For example, if the controlling workload has failed, a new instance can be provisioned in the private cloud (or a passive node can be activated) to take over the normal scheduled operations, and in this case the recovery is possible without rescheduling. On the other hand, if there is a hardware error that cannot be recovered at the cloud level a reschedule operation is done, usually in real time at the shop floor. Considering a CoBASA-type shop floor architecture [8], the handling of the resource breakdown is done by shop floor re-engineering techniques based on the resource (robot) consortium concept. When a virtualized Manufacturing Resource Agent (MRA) detects that the physical robot has malfunctioned or if the MRA itself crashed, the Coordinating Agent (CA) generates a resource breakdown event to the event listener. The event listener will handle the event by evaluating the mapping and executing the associated action in order to replace the failed resource (if the failure is recoverable or is in the software side).

The *rush order* event is generated when the COM module accepts an urgent order from a customer. This rush orders will usually cause the system to move from hierarchical to heterarchical operation mode [9, 10]. The redundancy action manager will handle this by evaluating the mappings and the rules that reflect the heterachical operation of virtual consortiums based on a default configuration. The implementing actions consist in re planning of batches, re-computing the order in which products are entered in the manufacturing cell and rescheduling the operations within each product together with reallocation of resources to each operation. If this is possible, or in other words, if the manufacturing cell has enough capacity to handle the rush order in the requested time-span, then no supplemental resources are added. If this is not the case, then more resources are added in the resource consortium at CoBASA-mechanism level. Corresponding to these hardware resources, the software resources are provisioned in the private cloud according to the redundancy profiles.

The redundancy profiles used by the redundancy action manager can be nested and so these map directly to the resource (robot) consortium (RC) concept in CoBASA. In practice resource allocation can be associated to a consortium rather than to individual items, which makes the solution manageable in specific integrations. The same concept applies when creating redundancy profiles for other MES implementations like IBM MIF or other solutions, both academic and commercial [11–13]. The creation of the redundancy profiles results from the enterprise deployment architecture where each workload is configured for high availability, depending on the specific role in the software solution and individual requirements.

4 Pilot Implementations and Experimental Results

The application example in this section explains how an existing vMES implementation prototype, in this case based on CoBASA-type architecture, could be enhanced with the redundancy mechanism presented in this paper.

The CoBASA architecture introduces an agent-based control architecture in which cooperation regulated by contracts is proposed as a flexible approach to dynamic shop floor reengineering. It describes the dynamic and flexible cooperation of manufacturing agents representing resources (here robots), and how they can be created from a generic agent template. The flexibility is assured by the

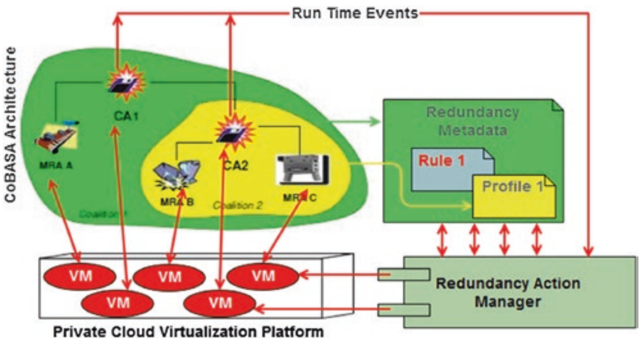

Fig. 2 Redundancy in virtualized CoBASA-type resource team reconfiguring in vMES implementation

resource (robot) consortium concept defined in the CoBASA-type architecture. In our implementation example below, the Redundancy Action Manager module uses a direct association between the Manufacturing Resource Agent consortium (robot team) and the redundancy profiles defined as shown in Fig. 2. The event sequencer receives events from the Manufacturing Resource Agents (MRAs) to gather real time information on robot availability and status and with the Customer Order Management (COM) module to determine capacity requirements. Based on the event mappings specified by the configuration engineers, the redundancy action manager generates actions that invoke the private cloud APIs to assure event handling and solution redundancy.

The Coordinating Agent (CA), as defined in the CoBASA-type architecture, has the role of generating run time events to the event listener module, in order to allow reconfiguration of the shop floor control architecture. While the CoBASA-type resource team reconfiguring vMES architecture is very well suited for implementation of the redundancy mechanism provided in this paper, in practice similar mappings between events and redundancy profiles can be implemented with almost any decentralized vMES implementation. While virtualization itself does not alter or enhance the functionality of the MES implementation used, it does enhance some non functional characteristics, like configuration flexibility, scalability and redundancy.

A series of redundancy tests were performed using an IBM CloudBurst 2.1 private cloud implementation and a pilot manufacturing cell consisting of six Adept robots and a closed loop conveyor. The tests show the recovery time for a resource type workload in active/active scenario and in active/passive for a resource breakdown scenario.

The experimental results presented in Fig. 3 show the downtime minimization achieved by the active/active configuration in separate cloud blades. The down time for this recoverable resource breakdown consists in the time from the breakdown event until the reconfiguration on node 2 is completed. In an active/ passive implementation this time will also have the provisioning time associated

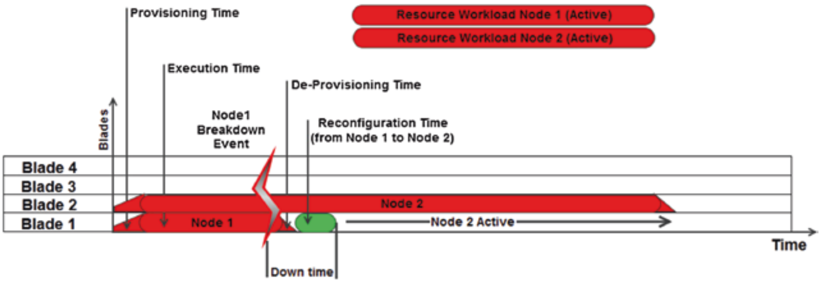

Fig. 3 Redundancy downtime in resource breakdown scenario with active/active configuration

to the node 2. For high risk workloads that involve real time operations, an active/active configuration allows minimization of the downtime. In an active/passive scenario, this downtime would be higher, but still significantly lower than a physical implementation.

5 Conclusions

Manufacturing system virtualization allows the separation between the physical resource and the controlling information system. Along with many operational and design advantages, a redundancy mechanism with active/active or active/passive workloads can be implemented with virtualized resources. In traditional implementations of manufacturing cells the implementation of controller redundancy involves using a separate physical workstation, and so it has a high operational overhead and a significant cost. However, without workload redundancy it is impossible to assure high availability for resources individually and for the entire solution. In other words, if the workload or workstation faced a problem at runtime, the whole shop floor resource would become unavailable. A private cloud implementation would be able to detect a workload failure and switch to the redundant workload in a very short time, assuring a high uptime for the manufacturing system. Virtualization brings many advantages also on the manufacturing system reliability by allowing full system snapshots and backups and quick recovery in case of failures, as well as providing built-in redundancy. Most private cloud implementations offer these features by default and can be directly adopted. Workload virtualization allows a separation or decoupling between the physical resource and the information system. The most important advantage introduced by decoupling is the possibility to have multiple versions of the virtual controller with different configurations and switch between them as needed.

Future work is focused on expanding the mechanism presented in this paper to support redundancy plans across different geographical locations of private clouds in order to support disaster recovery scenarios, thus assuring new levels of redundancy for large scale manufacturing enterprises.

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Manufacturing Operations, Internet of Things, and Big Data: Towards Predictive Manufacturing Systems

Radu F. Babiceanu and Remzi Seker

Abstract The recent leap advances in sensor and communication technologies made possible the Internet connectivity of the physical world: the Internet of Things, where not only documents and images are created, shared, or modified in the cyberspace, but also the physical resources interact over Internet and make decisions based on shared communication. The Big Data revolution has set the stage for the use of large data sets to predict the behaviour of consumers, organizations, and markets, taking into account the real-time outcomes of complex or unexpected events. Manufacturing can benefit from both these advances and move the manufacturing community closer towards the predictive manufacturing systems paradigm. Prediction in manufacturing operations could vary from simple resource failure prediction to more complex predictions of consumer behaviour and adaptation of manufacturing operations to address the expected changes in the business environment.

Keywords Sensor-based real-time monitoring · Big Data · Internet of Things · Predictive manufacturing systems

1 Introduction

The advances of sensor and communication technologies made possible the continuous monitoring of manufacturing and logistics activities through the use of networks of wireless sensors, RFID tags and readers, and GPS systems [1]. However, the monitoring capabilities provided by these technologies are limited in

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R.F. Babiceanu (✉) · R. Seker
Department of Electrical, Computer, Software, and Systems Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA
e-mail: babicear@erau.edu

R. Seker
e-mail: sekerr@erau.edu

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scope within the manufacturing enterprise, in the sense that they cannot be shared freely over large networks. With the advent of the Internet of Things, manufacturing enterprises could also make all the sensor data, and any processed information for that matter, available to the entities needing it and at the time it is needed. Basically, the Internet of Things uses a plug-and-play approach to not only link together computers that share and process data, but also to connect to the Internet any physical objects that have sensors attached to them for data collection and monitoring.

A manufacturing cyber-physical system is composed of the actual physical manufacturing system that, through the existence of sensor-packed objects, it is actually linked to the Internet of Things. This way, the manufacturing cyber-physical system can share, use, process, or alter data as recommended by its powerful algorithms powered by Big Data analytics. Within this framework, the cyber part of the manufacturing cyber-physical system is also the place for prediction modeling. Big Data analytics and complex event processing approaches are the engines for simulated scenarios in the search for the right answer to respond to the impeding event or aggregation of events, as well as the identification of that next event to happen, before it actually happens.

This work presents the framework for the development of a manufacturing cyber-physical system that includes capabilities for attaching to the Internet of Things, capabilities for complex event processing and Big Data algorithmic analytics and which is expected to move manufacturing closer towards the predictive manufacturing systems paradigm. From this point forward the paper is structured as follows: Sect. 2 provides a review of the most important aspects of the Internet of Things, Big Data analytics and predictive manufacturing systems, and after that Sect. 3 provides a first look at the modeling aspects of the proposed predictive manufacturing system detailing certain critical modeling aspects of it, such as the prediction of the time remaining until next resource failure occurs. Finally, the future research concerning the proposed predictive manufacturing system and enabling technologies are outlined in the conclusions section.

2 Literature Review

2.1 Brief Review on Internet of Things

In the recent years, with the advances in sensor and communication technologies, there is a surge in the volume of literature in the areas of Internet of Things and Cyber-Physical Systems [2]. Lagging a little bit behind, the manufacturing literature covering the areas of Internet of Things and Cyber-Physical Systems is just starting to pick-up in volume. Prabhu [3] states that the Internet of Things paradigm is set to revolutionize our world. The emerging Internet of Things technology enables human operators and decision-makers to talk to the physical objects, as well as enables the physical objects to talk to the human operators and decision-makers. Every electronic device, not just computers and networks, can send and receive data [4]. These operational communication segments are made possible by the multitude of sensor types currently available and take place over the already deployed and growing wireless and cloud cyber-infrastructure [5, 6]. Given the sensitivity of manufacturing design data and business analysis, the communication must be made over secure transmission media.

Within the Internet of Things framework, these sensors and sensor networks, such as RFID tags and readers, real-time process monitoring and control sensors, structural health monitoring sensors, inventory monitoring and control sensors, and so on, act as a bridge between the Internet and the physical objects (i.e., manufacturing resources, facilities, and equipment, as well as physical inventory of raw materials, work-in-process, and finished products). These sensors practically become the interface between the physical world and the cyber world, and are able to provide status control and adjustment to any stages of the manufacturing operational environment. Moreover, these sensors can also be viewed as the middle layer of the so called manufacturing cyber-physical system.

2.2 Brief Review on Big Data Analytics

Big Data has received a lot of attention in the last years considering its potential to change the regular way business operations are conducted in many domains. However, as Manovich [7] argues, Big Data is in many uses a poor term. The label of Big Data has been placed initially on large data sets that need high performance computing power, while currently very large sets of data can be analysed on desktop computers with standard software. From this point of view, Big Data may be better identified from the linkage that it may have with other aggregated data. The resulting complexity asks for the use of distributed computing to tackle the amount of computation.

The Big Data three-V's labelling framework for large data sets (Volume, Variety, and Velocity) is well known for some time and recently acknowledged in the comprehensive Big Data survey of Mayer-Schonberger and Cukier [8]. Berman, however, attempted at the enhancement of this Big Data characterization by adding three more dimensions to the first three V's, namely: Value, Verification, and Validation [9]. Adding three new dimensions to characterize Big Data may come with certain limitations regarding what type of data can be actually labelled as Big Data. But, from the manufacturing operations point of view, these added dimensions do not make the labelling of Big Data restrictive since manufacturing operations, system modeling and optimization, and system performance are all rooted in the system value and engineering verification and validation processes.

2.3 Brief Review on Predictive Manufacturing Systems

During operations, modern manufacturing equipment generates large amounts of data; however most of these data still remain uncollected. If these data could be collected and analysed, they would provide important information and strategies for productivity improvement and future operational conditions. Predictive manufacturing is a new paradigm that was made possible by the recent advances in computing and communication technologies and is enabled by technologies such as RFID, wireless sensor networks, computing in the cloud, advanced analytics, cyber-physical systems, Internet of Things and Big Data. Lee et al. [10] describes traditional manufacturing operations based on a 5M approach:

- Materials: represented by properties and functions.
- Machines: represented by precision and capabilities.
- Methods: represented by efficiency and productivity.
- Measurements: represented by sensing and improvement.
- Modeling: represented by optimization, and prevention.

However, due to the leap advances in computational power and data processing capabilities, more data of different types can be made available to the manufacturing system analyst. Considering these new data available, Lee et al. [10] propose a new view for manufacturing operations, and characterize manufacturing operations using also a 5C framework, as depicted below:

- *Connection*: represented by Big Data volume generated by deployed sensors and networks.
- *Cloud*: represented by Big Data velocity with computing data available on demand and anytime.
- *Content*: represented by Big Data insights through data analysis, correlation, and meaning.
- *Community*: represented by the Big Data variety coming from data sharing and social networking data.
- *Customization*: represented by Big Data analytics enabling personalization and value.

The development of the Internet of Things, with its physical objects connection to the Internet through the use of smart sensors, smart resources, smart shop-floor, and telecommunications had an important role in the emergence of the predictive manufacturing paradigm. Multi-agent distributed systems concept is the methodology of choice for modeling the smart objects and is situated at the core of the predictive manufacturing technology [11]. In more detail, the smart physical objects, linked to the Internet of Things, are run by smart software segments that conduct predictive modeling functionalities and recommend actions to be taken by the manufacturing cyber-physical system.

3 Framework for the Development of Predictive Manufacturing Systems

3.1 Predictive Manufacturing Systems

Building on the existing manufacturing cyber-physical system paradigm, with its simulation monitoring, complex event processing, and prediction modeling capabilities, this research aims at laying the foundations for prediction in manufacturing operations. The current technology, through the envisioned Internet of Things, can provide the analyst more data than ever before. Types of data to be collected from a manufacturing facility may include: identification data, operational data, diagnostic data, process data, and environmental data [4]. Also, social networks applications can provide large amounts of data and analytics software can uncover valuable information. By analysing all the collected data there is potential for prediction and prevention in the manufacturing domain.

The predictive manufacturing system is expected to be able to predict the occurrence of undesired events and recommend changes of the operational status to either bypass the undesired event or avoid it, with expected operational and competitive advantages for the manufacturing enterprise. At the same time, the predictive manufacturing system is expected to be able to predict future opportunities and recommend changes of the operational status and resource utilization to leverage on the coming opportunities and benefit from the resulting operational and competitive advantage situations.

3.2 Prediction of Manufacturing Event Occurrences with the R Programming Language

A first example of predictive manufacturing operations is presented next. The example provides insights in future resource and facility performance and estimation of the main performance measures used in reliability engineering: the mean time to failure (MTTF) and mean time between failures (MTBF). Using the predicted failure data generated by the prediction algorithm, changes of the operational status can be made in time before the occurrence of the actual detrimental event. The changes are expected to result in the protection of facilities, resources, work-in-process, quality of products, and consequently safeguarding the competitive advantage of the manufacturing enterprise.

The predictive manufacturing operations decision-making process uses Big Data analytics and algorithms that can be implemented in new powerful languages such as R. The R language is a high-level programming language that provides flexible statistical, data analysis, and visualization capabilities [12]. A recent survey reported by Prajapati [13] suggests that R recently became the most popular language for data mining and analytics. Also, R comes with an appropriate algorithmic approach to address the challenges posed by the increasingly large and complex sets of data, thus it is suitable to analyse the Big Data streams generated by the predictive manufacturing system operations.

For example, the above mentioned MTTF and MTBF can be calculated using individual time to failure estimations of the manufacturing resources on the shop-floor. The time to failure can be modelled in R using functions such as, the native to R, survival modeling function, included in the `survival` library [14]. Considering manufacturing resources equipped with networks of sensors that monitor a certain resource life parameter and which generated a set of 100 historical life time data, the survival function is able at any time to identify the time between any two consecutive failures, and the time elapsed from the last failure, as depicted in the next segment of code, where `Surv` is an R object created to represent survival information.

```
library(survival)
FailureDataSet.Surv <- transform(FailureDataSet,
    surv=Surv(
          time=FailureDataSet$time.to.failure,
          event=FailureDataSet$disturbance,
          type="fleming-harrington"
   )
)
FailureDataSet.Surv$surv[1:100]
```

Survival analysis is concerned with identifying the amount of time that elapses before an event occurs, such as the time before a failure occurs for mechanical systems, the amount of time before a consumer cancels an account in marketing, etc. [14]. In the example above, survival analysis could be used to predict the amount of time until the next resource failure occurs. R includes a variety of functions in the `survival` library for modeling survival data. To estimate a survival curve, the R `survfit` function can be used as follows:

```
library(survival)
FailureDataSet.survfit <- survfit(
    formula=surv~sensor.status,
    data=FailureDataSet.Surv,
)
plot(FailureDataSet.survfit)
```

Also, to predict the expected survival time for a set of resources, the R `survexp` function can be used in a similar manner.

```
library(survival)
FailureDataSet.survexp <- survexp(
    formula=surv~sensor.status,
    data=FailureDataSet.Surv,
    time=time.to.failure,
)
print(survexp)
```

3.3 Integrating R with Big Data Analytics

As mentioned in the previous section, R is a powerful high-level programming language that provides data analytics and visualization capabilities. To move closer to the identified objective of predictive manufacturing paradigm, one needs to add capabilities of Big Data processing to the R language capabilities. Over the years, Apache Hadoop became the environment of choice for Big Data storing, processing, and analysis [15]. Currently there are several different environments that are based on Hadoop, such as HIVE, YARN, etc. The need for integration between R and Hadoop gave rise to environments such as RHIPE and Ricardo [16]. Using Hadoop's distributed file system (HDFS) and its Map/Reduce distributed computation framework, analytics, such as behaviour prediction, can be performed on large amounts of collected data. One limitation of Hadoop and its associated computational platforms is the relatively low computational speed, which for many of the manufacturing and supply chain operations may be disadvantageous, as real-time response is sought after to keep organizations' competitive advantage. Open source platforms such as Lustre are reported to be as much as three times faster than those based on HDFS at processing Big Data analytics jobs [17].

Considering historical data representing the same instantiation of a manufacturing system as above, which includes a large number of manufacturing resources and processes, manufacturing operations behaviour prediction can be modelled using the R `randomForest` function that combines sets of different tree models obtained through distributed computation and averages them together to define a single prediction model.

```
library(survival)
library(randomForest)
PredictionModel.randomforest <- randomForest (
    formula=FailureDataSetFormula,
    data=FailureDataSet.Surv,
    na.action=na.omit
)
print(PredictionModel.randomforest)
```

4 Conclusions and Future Research Directions

This work provides initial guidelines regarding the nature and architecture of predictive manufacturing systems as an added benefit of the development of the manufacturing cyber-physical systems. Currently, operational prediction in manufacturing is still in its infancy. However, with the increase in the number of smart objects linked at the envisioned Internet of Things and further enhancement of the Big Data analytics algorithms, the operational prediction in manufacturing could become a reality in the next years. Future work will concentrate on developing Big Data algorithms appropriate for manufacturing operations and building simulation models, running as part of the cloud manufacturing, which are capable for hinting at operational prediction in manufacturing Big Data environments. Particular attention will be given to identify the appropriate computational platforms for manufacturing Big Data analytics, as the most popular Big Data analytics platforms in use today have the serious limitation of being too slow for processing manufacturing environment data.

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Manufacturing Cyber-Physical Systems Enabled by Complex Event Processing and Big Data Environments: A Framework for Development

Radu F. Babiceanu and Remzi Seker

Abstract The decades old manufacturing operations question of choosing the right answer in the face of disturbances created by certain unexpected events, or by their aggregation, could now be one step further to receive the right answer. A sensor-packed manufacturing system in which each process or piece of equipment makes available event and status information, coupled with market research for true advanced Big Data analytics, seem to be the right ingredients for event response selection, and thus moving manufacturing closer to the cloud manufacturing systems paradigm. Besides the inherent obvious advantages that come with the cloud manufacturing capabilities, the resulting manufacturing cyber-physical system will be also subjected to the known setbacks of the software and Internet-based systems, from which cyber-security needs to be addressed at the forefront.

Keywords Sensor-based real-time monitoring · Complex event processing · Big Data · Cloud manufacturing

1 Introduction

Operations research and computer science provided successful solutions for manufacturing shop-floor problems for many years. Productivity increase, cost reductions, real-time job scheduling and many other objectives can be optimized with the help of different operations research and computer science algorithms and methodologies. These solutions, however, usually come with a caveat; one big caveat. These elegant and powerful models are defenceless when unexpected

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R.F. Babiceanu (✉) · R. Seker
Department of Electrical, Computer, Software, and Systems Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA
e-mail: babicear@erau.edu

R. Seker
e-mail: sekerr@erau.edu

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events come into play. As a result, practitioners have usually either resorted to, after the fact, corrective solutions in order to reduce and contain the potential negative effects, or proactive (preventive) solutions that employ the use of redundancy approaches to continue the operations in certain situations.

The current manufacturing global operations asks for more and stringent requirements than ever before, such as strict deadlines, low inventories, uncertain demand, standardization of manufacturing processes, and product diversity, to name a few [1]. Enhancing the manufacturing environment for more visibility and better control of the production processes becomes essential. Advances in sensor and communication technologies can provide the foundations for linking the physical facility and machine world to the cyber world of Internet applications and software world. The coupled manufacturing cyber-physical system could be designed to handle the actual operations in the physical world while simultaneously monitor them in the cyber world with the help of advanced data processing and simulation models at both the manufacturing process and system operational levels.

This work presents the framework for the development of a manufacturing cyber-physical system that includes capabilities for complex event processing and Big Data analytics, which is expected to move manufacturing domain closer towards the digital manufacturing or cloud manufacturing systems goal. In the enterprise context, cloud solutions usually consider the business layer and address the needed tighter interaction with the customer and the integration with suppliers, competition, and regulatory bodies. Thus, building on already developed cloud business solutions, cloud manufacturing is expected to offer improved enterprise manufacturing and business decision support. From this point forward the paper is structured as follows: Sect. 2 provides a review of the most important aspects of the Big Data analytics and complex event processing, and after that, Sect. 3 presents the proposed modeling framework for the cyber-physical manufacturing system detailing certain critical modeling aspects and instantiates the cloud manufacturing systems paradigm. Finally, the future research concerning the proposed cyber-physical system framework is outlined in the conclusions section.

2 Literature Review

2.1 Brief Review on Big Data Analytics

The global Big Data market estimated in the supply chain operations domain was around $0.43B in 2012, with a contribution of 24 % coming from the manufacturing supply chain sector. The entire market is expected to reach $3.73B by 2018, with the manufacturing supply chain expected to contribute with over $1B. Other important contributions will be coming from the retail and services sectors [2]. The well-established computing and data analytics literature characterizes Big Data as data having three distinct dimensions, or three V's [3].

- *Volume*: dimension measured by the large amounts of data generated, easily accounting for terabytes of data.
- *Variety*: dimension measured by the different types of data generated, with both structured and unstructured data of all sorts, such as text, audio, video, images, log files, and so on.
- *Velocity*: dimension measured by the constant accumulation of new generated data, which need to be processed as soon as received to maximize the value to the organization.

Current global operations and competitive business environment force manufacturing organizations to address all these three dimensions. While the volume and velocity dimensions are already known to be of paramount importance, the other dimension of variety is just starting to prove its importance for manufacturing organizations to be able to successfully compete on the global arena. Berman [4] adds another three dimensions (interestingly, identified as V's, as well) to characterize Big Data and which could prove to be extremely valuable for manufacturing organizations, presented below.

- *Vision*: dimension measured by the purpose of the process which generates the data; other works define this dimension as the value of Big Data, which is somehow similar, as an entity's vision is expected to provide avenues for value identification.
- *Verification*: dimension measured by the conformance of the generated data to a set of specifications; this dimension, applied to data analysis, serves the same purpose as the engineering verification process.
- *Validation*: dimension measured by the conformance of the generated data with the defined vision; this data analysis dimension is to some extent similar in purpose to the engineering validation process, with the added element of covering also the potential results from data analysis, which cannot be determined beforehand.

Davenport [5] argues that when seen as just numbers, Big Data does not mean too much to the average business person or manufacturing decision-maker, but the insights offered by processing Big Data may prove extremely valuable. At the same time, besides opportunities, Big Data also comes with certain associated costs, such as cost of data processing, and the hiring cost of IT professionals and data analysts. Loshin [6] touches on the Big Data tools and techniques currently in use for different applications that leverage the combination of collections of four key computing resources: process capability, memory, storage, and network. Big Data tools currently in use include: Hadoop Distributed File System (HDFS), MapReduce, YARN, HBase, HiveQL, NoSQL, etc. [6].

2.2 *Brief Review on Complex Event Processing*

In the traditional understanding of manufacturing operations, an event is defined as an action, activity, or change in a parameter that influences an existing operational status of the manufacturing system. Generally, event processing means tracking, processing and analysis of event data and deriving reliable conclusion from the analysis. Within the Internet of Things (IoT) framework, Prabhu [7] defines a simple RFID reading event as the triple (sensor ID, object ID, time), where the time at which the tracked object passes through the reading space of the sensor is collected and transmitted. When multiple time-ordered simple events occur, the resulting sequence of events is viewed as a complex event. On a larger scale, complex event processing is defined as the use of technology to predict high-level events, resulting from the combination of data from multiple sources, which could be made of other events, factors, or patterns. The objective of complex event processing is coined by Luckham [8] as to identify meaningful events, both opportunities and/or threats, and provide the right answer in the least amount of time possible.

3 The Manufacturing Enterprise as a Cyber-Physical System

3.1 Proposed Manufacturing Cyber-Physical System Framework

Previous work in the area of distributed manufacturing systems identified RFID, wireless sensor networks, and cloud computing as enabling technologies for the development of reliable monitoring and control systems for manufacturing operations [9]. In another work, one methodology for complex event processing in manufacturing and service enterprise systems environments was derived together with modelling and simulation approaches for behaviour prediction [10]. This work proposes a further step towards modeling and simulation for real-time operational monitoring and control in manufacturing environments. The cyber-physical manufacturing system is based on both the physical world, where the traditional manufacturing system resides, and the cyber world, where the Internet and computing in the cloud takes place. Interfacing the two worlds, there is a multitude of sensors and networking that complete the cyber-physical system framework, as depicted in Fig. 1.

The cloud manufacturing system forms the cyber world and works as the digital mirror image, of the actual system that comprises the physical world. The cyber manufacturing system operates in the cloud and simulates the manufacturing operations and continuously monitors the facility and resource status using integrated data and information from both sensor data driven algorithms as well as available physical data. Thus, the cloud manufacturing system provides real-time manufacturing operational and resource condition status on demand, which is especially advantageous when physical access to manufacturing shop-floor status and data are limited.

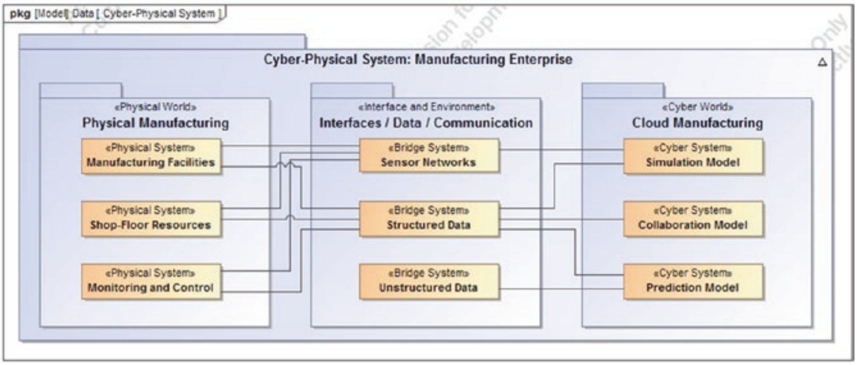

Fig. 1 The manufacturing enterprise as a cyber-physical system, with the physical manufacturing, cloud manufacturing, and the interface between the two worlds together with the external manufacturing environment

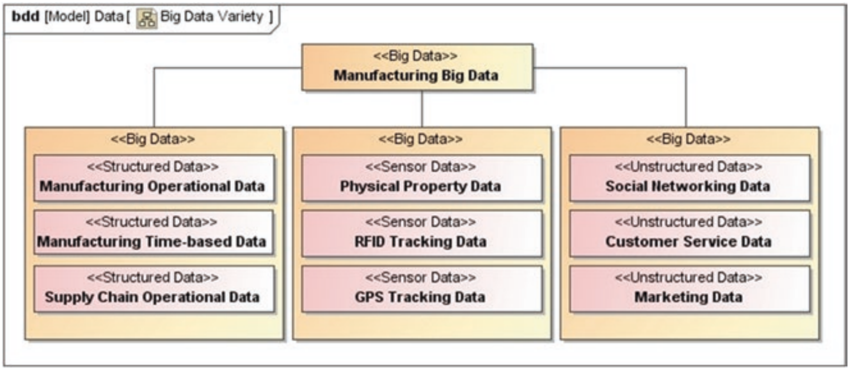

Fig. 2 Manufacturing Big Data variety with traditional structured manufacturing operational and time-based data, sensor data, and unstructured data

3.2 Big Data and the Manufacturing Cyber-Physical System

Structured traditional manufacturing operations data together with sensor and environment data and unstructured marketing and social networking data comprise the bulk of the manufacturing Big Data. Figure 2 outlines the variety dimension of manufacturing Big Data. Algorithms designed for manufacturing Big Data processing, analysis, scoring and assessment need to take all the 3 + 3 Big Data "V" dimensions depicted in Sect. 2. The expected advantages coming from the use of Big Data in manufacturing enterprise settings are presented below:

- Real-time monitoring and control of manufacturing operations, such as production planning and scheduling, inventory control, supply chain coordination, as well as resource, process, and tooling status.

- Understanding the enterprise performance on multiple metrics, and identifying the best combination of manufacturing and other enterprise data, to improve enterprise metrics such as energy efficiency and cost control.
- Ability to predict the occurrence of undesired events and to find solutions for real-time rescheduling of manufacturing operations in the face of disturbances resulting in reduced shipment delays and quality improvement of the finished products.
- Improved prototyping, testing, and, where appropriate, production of finished products through the inclusion of unstructured data analytics and the use of 3D printing capabilities.

As usual, associated with important opportunities there are likely significant challenges, as well, that need to be mitigated in the process of implementing the new technology. Big Data analytics for manufacturing operations will need to address challenges such as:

- Security of sharing data across the enterprise and over wired and wireless networks with external collaborators geographical distributed and subject to specific policies and regulations.
- Changing the enterprise culture of traditional decision-making to Big Data-based decision-making, which include building trust between Big Data analysts and manufacturing managers, and identifying on case by case basis the level to which Big Data analysis suggestions should be implemented in manufacturing practice.
- Hiring the right Big Data analysts that, besides having appropriate Big Data analytics skills, understand manufacturing and supply chain operations, and the global operational context.

3.3 Complex Event Processing for the Manufacturing Cyber-Physical System

During their operations manufacturing systems are constantly subjected to events (new orders, machine breakdowns, tooling wear-out, market changes, sensor reading, just to name a few) and their consequences. Discrete-event simulation provides the framework for modeling and analysis of these events and it was used for several decades to obtain insight and optimize manufacturing operations. However, in certain situations, the cumulative action of multiple different types of events, occurring within the same time unit, can lead to consequences that cannot be modelled directly as resulting from the individual constituent events. Processing of the resulting sequence of events must be performed taking in consideration all the individual events together with their potential interactions and consequences.

Complex event processing method is appropriate for modeling these types of systems subjected to the sequence of events. Complex event processing is naturally a network approach were multiple types of events, together with other factors

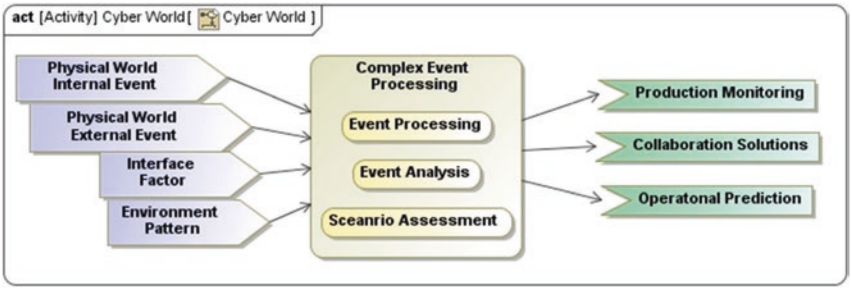

Fig. 3 Complex event processing in the cyber world based on physical world, interface and environment events, factors, and patterns

and identified patterns are considered in order to infer the needed real-time or near real-time resultant system response. It is expected that processing those events in the network environment, events that could be system opportunities, system threats, or a combination of them, will provide operational visibility and awareness for the manufacturing system. The complex event processing is depicted in Fig. 3, where different types of events, factors, characteristics, parameters or patterns are the inputs for three cyber world models, and results in the following three outputs.

- *Production monitoring*: realized through the continuous monitoring in the cyber world of the actual manufacturing operations taking place in the physical world through simulation models fed by aggregation of events, environment patterns, and system interface factors.
- *Collaboration solutions*: realized through the assessment of the computed scored cyber world recommendations for collaboration solutions with organizations acting in the physical world in order to increase the positive trend for the performance measures selected for improvement.
- *Operational prediction*: realized through the awareness and implementation of recommendations to be followed by the physical world manufacturing system in order to enhance system opportunities or thwart potential threats directed toward the manufacturing system.

Complex event processing includes three separate activities: event processing where the received data is processed and converted in the format needed for analysis; event analysis, where data analytics and Big Data analytics are employed to generate operational scenarios; and scenario assessment, where the generated scenarios are scored-ranked and recommendation are made for situational awareness and operational solutions. The volume, variety, and velocity of data generation require adequate analytical tools which may not be available for manufacturing and supply chain participants, but can be imported from the Big Data analytics methodologies. Since, many times, the Big Data analytics methodologies are reported to be slow, emphasis should be centred on those Big Data tools that include fast processing capabilities, as manufacturing and supply chain operations need adequate response in face of unexpected events.

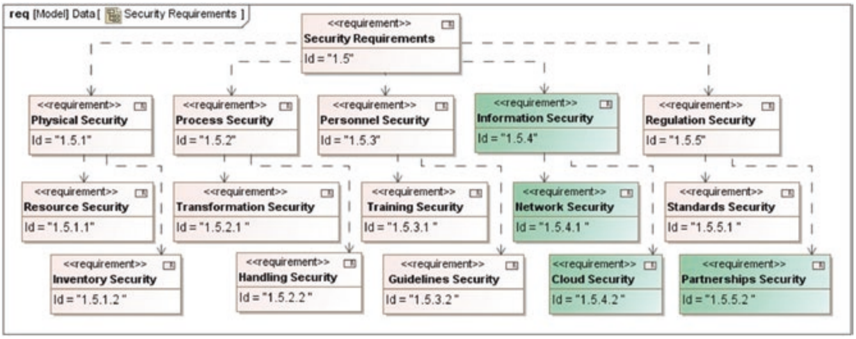

Fig. 4 Security requirements for the cyber-physical manufacturing system as part of the security requirements for the entire manufacturing cyber-physical system

3.4 Cyber-Security in the Context of the Manufacturing Cyber-Physical System Framework

Two of the three pillars of the proposed manufacturing cyber-physical system include intense cyber networking, data processing, and communication. Besides the inherent advantages, the heavy emphasize on computing and computation also presents real challenges from the data protection point of view. Hence, the manufacturing cyber-physical system's weighty focus on cyber-security. Price Waterhouse Coopers [11] identified the security aspects for distributed supply chain systems. Building on that foundation, Fig. 4 outlines the security requirements for the entire manufacturing cyber-physical system. While the security of the physical world is well studied and standards and regulations are in place for a long time, it is the cyber world security that requires continuously updating due to the nature of ever changing threats of the cyber world.

The direct cyber world security, or cyber-security, aspects such as information security, network security, and cloud security, as well as the indirect cyber-security aspects such as partnership security, through information sharing and collaboration, are highlighted in Fig. 4 and will be studied in a future work.

4 Conclusions and Future Research Directions

This work presents a framework for the development of a manufacturing cyber-physical system, where the manufacturing operations taking place in the physical world are mimicked in the cyber world part of the system. The bridge between the two worlds is provided by networks of sensors, communication capabilities, and external data, information, and knowledge. The simulated operations taking place in the cyber world can provide powerful insights related to the actual operations and help in re-routing of the operations based on status of manufacturing facilities, resources, tooling, and available business operation data. Big Data analytics is employed to make sense of the large amounts of data generated by the sensor-packed manufacturing operations and consumer trends collected from social networking and marketing data. Future work will focus in detailing the system architecture, provide insights on the Big Data analytics algorithms, and simulate the operation of the cyber world system. Appropriate Big Data analytics platforms capable of providing the required output flow needed for manufacturing operations will be suggested. Also, specific cyber-security aspects mandatory for actual cyber-physical systems deployments will be identified.

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Planning and Control of Maintenance, Repair and Overhaul Operations of a Fleet of Complex Transportation Systems: A Cyber-Physical System Approach

D. Trentesaux, T. Knothe, G. Branger and K. Fischer

Abstract In this paper a new architecture named CPS4MRO, that goes a step further previous research development and industry-oriented projects led by the authors, is specified. The aim is to provide in the near future an optimized planning and control of MRO operations of a fleet of complex transportation systems using the paradigm of Cyber-Physical Systems.

Keywords Maintenance · Repair · Overhaul · Cyber-physical systems · Planning · Control · Transportation systems · Complex moving systems

1 Introduction

The convergence of the embedded and Internet world has led to the concept of *Cyber-Physical Systems* (CPS). This refers to interconnected ICT systems (including through the internet) that are embedded in- or connected with physical objects (like products, machines and humans), which provide citizens and businesses with a wide range of innovative applications and services. This convergence may also exploit the growing Internet of Things (IoT) and smart devices of the future and triggers the next round of innovation towards intelligent and autonomous systems [1].

D. Trentesaux (✉)
LAMIH UMR CNRS 8201, UVHC, Valenciennes 59313, France
e-mail: Damien.Trentesaux@univ-valenciennes.fr

T. Knothe
Fraunhofer Institute for Production Systems and Design Technologies, Berlin, Germany
e-mail: Thomas.Knothe@ipk.fraunhofer.de

G. Branger
Bombardier Transportation, Crespin, France
e-mail: guillaume.branger@fr.transport.bombardier.com

K. Fischer
Research Center for Artificial Intelligence, DFKI GmbH, Saarbrücken, Germany
e-mail: Klaus.Fischer@dfki.de

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In this paper the application of CPS for planning and control of maintenance repair and overhaul processes for transportation systems is explained. The current circumstances in these sectors are driving companies to more intensive process orientation. Tom Enders, CEO of Airbus, recently affirmed that "nationality doesn't matter anymore" and that "best processes and methods" differentiate competitors [2].

Maintenance, Repair and Overhaul (MRO) providers have a strong influence on these factors through aligning the synchronization of MRO assets (qualification, spare parts and tools) with the transportation operation. A mid-sized European airline, for instance, currently has to conduct ten flight changes per day due to unforeseen or misaligned maintenance requirements. In contrast to static objects (like machine tool) transportation systems are "moving" MRO-targets, requiring the transportation of spare-parts, skilled mechanics and tools to locations away from the home base. Inefficient planning and control processes that run sequentially and are associated with a number of loops and interfaces between maintenance planning and the mechanical department, in addition to the required MRO activities, reduce the availability of crucial assets, increasing the complexity of operations and incurring avoidable cost.

In order to improve this situation, planning and control paradigms have to be modified and new equipment capabilities established. The substantial lifecycle times of electronic equipment for railways and aircrafts require new technologies and processes to function with existing equipment and infrastructure currently in place. The integration of sensors into existing machines and the use of smart items will provide the basis to advance the management of maintenance cycles.

Obviously, several researches have been led to provide efficient planning and control of preventive (scheduled) or curative (un-scheduled) maintenance of single *Complex Transportation System* (CTS), see for example in the train transportation industry [3, 4] or in the air craft industry [5]. But considering at an upper level a whole fleet of CTS increases drastically the complexity of planning and control of such operations, which is still a hard issue for industrials and fleet operators. In this paper, an innovative approach, based on previous experiences from the authors using Cyber-Physical System (CPS) paradigm, is specified to plan and to control the MRO operations of a fleet of CTS.

2 MRO of a Fleet of Complex Transportation Systems: Context

The **Fleet MRO** is a specific fleet management function whose activities are focused on the use phase of a fleet of CTS. It aims at ensuring a sufficient on-the-fly availability and reliability level of each element of the fleet as well as a sufficient quality of service at the fleet level.

For European CTS constructors and fleet operators, this function is getting more and more important because of two main reasons.

First, besides the dynamic development, the transportation market is under high cost pressure with new competitors entering the market. For example, European aviation operates in a highly competitive and global arena, in which other regions of the world, both established and emerging economies, have recognized the strategic nature of aviation and are developing capabilities along the entire value-chain from vehicles, through infrastructure, to services, all supported by significant investment. The threats from this competition are very dynamic and real, both within Europe and regarding exports on the global market. A steady influx of new competitors into the European transportation market increases the pressure on firms to reduce their costs. New entrants from Arabian sub-continent [6] in particular are forcing European transport providers to rethink their current global strategy. Tom Enders, CEO of Airbus, recently affirmed that "*nationality doesn't matter any-more*" and that "*best processes and methods*" differentiate competitors [2]. This emphasizes that the efficiency of processes and methodologies is a key to the sustained success of the European transport sector in the global market space. The situation in the rail industry is quite similar even here since the Asian countries are investing massively in R&D.

Second, the decrease of the quality of service, even at a short level and for a short time, leads to the risk of a high-speed degradation of the image of the service provider (fleet operator) among the customers. The reliability and availability of operating times of transportation systems are crucial success factors that can have significant impact on the service providers' competitive position in the market. As a consequence, for example in the rail transportation industry, when requesting for furniture proposals, service providers/operators ask now constructors to complete their offer with fleet maintenance services and solutions. This becomes a major drawback for constructors whose organization cannot propose such a service along with their fleet offer. Fleet MRO is nowadays a major issue addressed by both service providers/operators such as French SNCF and CTS constructors such as Bombardier.

Obviously, fleets of CTS, like any complex system, are subject to preventive and curative MRO whose operations are to be planned and control. But unlike static (non-moving) systems, several specific constraints can be identified when considering MRO activities of such systems:

- *CTS are moving systems*: In contrast to static objects (like machine tools) CTS are "moving" MRO-targets, requiring the transportation of spare-parts, skilled mechanics and tools to locations away from the home base, sometimes worldwide.
- *Facilities*: maintenance centres, maintenance skills, spare parts and tools may be located at different places worldwide, while CTS subjected to maintenance may be in another place, requiring for example meeting points for maintenance activities.
- *Diversity*: since the considered CTS have a long life time compared to maintenance cycles, the fleet is often composed of CTS with different technological solutions, including technological upgrades with different past use and maintenance histories. This technology diversity leads to a high diversity of the maintenance diagnosis, maintenance tasks, maintenance skills and maintenance facilities.
- *Dynamic fleet composition*: the composition of the fleet is not constant. It is increased through the successive buying/delivering of CTS and diminished through the removing of older CTS to be dismantled, which implies to reconsider dynamically the whole maintenance process of the fleet.

- *Liability*: when provided to the operator/service provider, CTS are always attached with warrantee conditions for a limited period. Thus in a fleet, they may co-exist under and out of warrantee CTS, making it harder to globally optimize the fleet maintenance. There is also needed, in case of a breakdown or a security problem, to seek for legal responsibilities.

In this context, and focusing on the planning and control activities, several issues can be identified. They are pointed out in the next section of the paper.

3 Planning and Control of MRO Tasks of a Fleet of CTS: Issues

The introduced context makes CTS MRO task planning and control a major stake for CTS constructors and fleet operators. First, given the huge exploitation costs of each CTS their unavailability for maintenance operation must be as limited as possible. Obviously, this can be true for any system requiring a correct balance between use and maintenance, but specifically in the addressed context operators/service providers and CTS manufacturers face now a limit forbidding them to increase the availability of their fleet only by adding new preventive maintenance tasks. As a consequence, new maintenance mechanisms must be found to increase the availability of the fleet while not increasing their under maintenance period.

Second, inefficient planning and control processes that run sequentially and are associated with a number of loops and interfaces between maintenance planning and mechanical department, in addition to the required MRO activities, reduce the availability of crucial assets, increasing the complexity of operations and incurring avoidable cost. MRO providers have a strong influence on these factors through aligning the synchronization of MRO assets (qualification, spare parts and tools) with the transportation operation. The mid-sized air-line Air Berlin, for instance, currently has to conduct ten flight changes per day due to unforeseen or misaligned maintenance requirements. In order to improve this situation, planning and control paradigms have to be modified and new equipment capabilities established. The substantial lifecycle times of electronic equipment for railways and aircrafts require new technologies and processes to function with existing equipment and infrastructure currently in place. The integration of sensors into existing machines and the use of smart items shall provide the basis to advance the management of maintenance cycles.

Meanwhile, the quantity of raw data gathered on the different CTS of the fleet in real time is huge, limiting reactivity in monitoring, thus in maintenance operations. More, data comes from CTS often scattered over a large geographical area, implying for example processing, time stamping, history, reliability analysis and localization issues for each of these raw data. Thus, if traceability actions are not correctly engaged in a complete way to memorize past maintenance activities on each CTS, this may lead to a rapid decrease of on-going planning and control maintenance decisions quality and pertinence. This “Big Data” context is a real issue for industrialists whose complex systems make them face human safety and time reaction as hard constraints (typically: transportation, manufacturing, health-care, energy…). When human safety is not a real-time issue (in communications, e-commerce, social networks, web services…), "Big Data" is not a problem but rather a chance: managers have time to mine data and to find out knowledge from raw data. In this first kind of industry, managers rather prefer to handle "**Small Data**" than "Big Data", because only small data and precise knowledge enable them to react quickly and efficiently while ensuring at the same time the human safety. Despite this, "Big Data"-orientation is currently the preferred approach in transportation mainly because of habits: it is the way engineers are used and taught to work. But when we analyse more precisely what happens in the transportation sector, it is easy to find out that raw data and error codes are gathered, stored into huge data warehouses, and forgotten because industrialists do not know how to handle this huge quantity of data. We call this principle the "*store and forget*" principle, by analogy with the famous "fire and forget" principle in military systems. Due to this, it often happens that a plane or a train had to come into a curative maintenance process because managers were not able to identify in due date the signal/information that was pointing out the risk of a failure.

Another problem related to the previous one is that most of CTS maintenance activities remain human-based. Obviously, the scheduling of maintenance activities are most of the time computerized, but except for air operators, not enough attention is paid to the memorization of what has been done or not exactly into information systems to improve planning and control of MRO tasks.

Despite this, the MRO trend study elaborated in 2011 is underlining the demand of new solutions; more than 30 % of MRO partners expect more improvement for MRO Planning and Control [7].

Among other, Cyber-Physical System is an innovative concept that enables to address this planning and control issue, seeking to increase the availability and to lower maintenance cost (with the same level of safety) as well as trying to generate "small data" instead of "big data". But from our point of view, existing solutions are a first step towards this but they are still not sufficient. To illustrate this, two industrial-based case studies (in airplane transportation and train transportation) from the past experience of the authors are presented and discussed, which will enable us to point out some required improvements.

4 CPS for MRO Tasks Planning and Control: Approach and Case Studies

4.1 Cyber-Physical Systems

Integrated networking, information processing, sensing and actuation capabilities allow physical devices to operate in changing environments. This makes smart systems possible but also creates the need for a new 'systems science' that can lead to unprecedented capabilities. Tightly coupled cyber and physical systems that exhibit this level of integrated intelligence are sometimes referred to as cyber-physical systems. According to [8], “*Cyber-Physical Systems (CPS) are integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa*”. CPS can be seen as a kind of generalization of the concept of an embedded system to a network of embedded systems [9]. Thus, for example, the concept of CPS is more general than the one of intelligent product in the use phase [10]. Modeling CPS requires the use of models able to consider at the same level of importance the digital word and the physical word. As a consequence, the holonic paradigms [11] and the physical agents one [12] suits well this modelling constraints while the “*system of systems*” paradigm [13] may help to structure the way CPS are designed in a safe way. Service orientation, internet of things and ambient intelligence proposes up-to-date technological solutions to implement CPS within the context of the smart grid [14]. Whilst the first integrated CPS for supporting self-organized control in manufacturing was developed and applied for demonstrators in 2010, CPS enabled intelligent communication and interaction between transportation systems were piloted already in 2008 [15]. For example, automatic collision systems already detecting moving objects and respond faster than a human operator.

To show the potential benefits of the CPS paradigm in MRO of CTS, two illustrations in the airplane and train transportation contexts are presented and analysed in the following sections of the paper.

4.2 CPS for MRO in Airplane Transportation : A First Case Study

In the airplane industry, specifically the usage of CPS for MRO planning and control with direct negotiation between transportation system and other MRO objects, has been discussed since 2012 [16], and some aspects have been described since 2010 [17]. For example, in [18] the change from vertical chain to direct communication is defined and underlined as a paradigm shift, with an execution architecture based on agent technologies (see Fig. 1).

The mentioned agent-based architecture supports the execution of negotiation between the entities contains five central functions: Escalation Management/Simulation to solve negotiation problems, Registries/Certification to ensure that only certified personal and tools can be assigned to maintenance tasks, Negotiation Control to observe all negotiations between entities and to filter irregular states (e.g. if a task needs more than 10 min to be assigned), transport planning view as well as the maintenance capacity planning, which has to be done still manually, even automatically aided by user data. On the other hand, each of the entities of the CTS being a mechanical system, spare part and tool owns a CPS with different capabilities as illustrated in Fig. 2. The CPS can be integrated into existing electronic equipment like the electronic flight bag system.

With the decentralized intelligence and direct task assignment the administrative processes can be cut-off drastically and new application scenarios are possible.

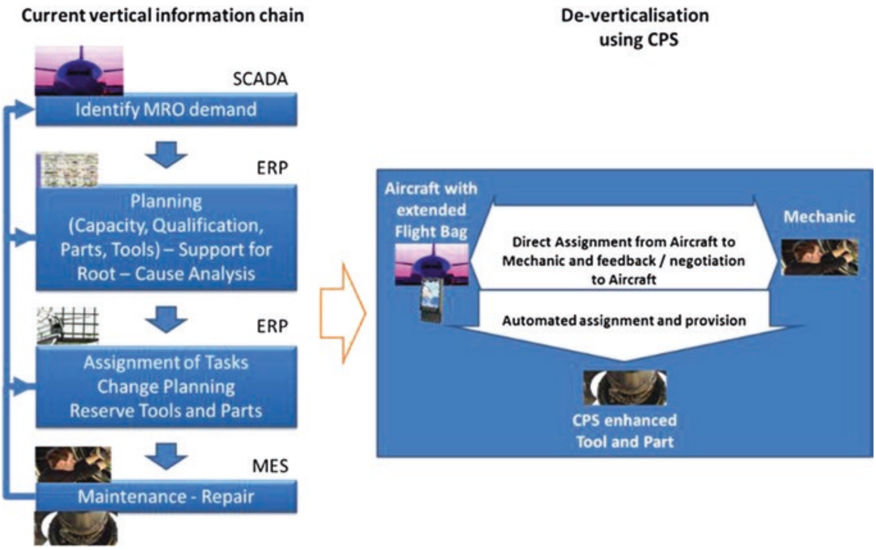

Fig. 1 Paradigm shift from vertical planning and control processes to direct negotiation

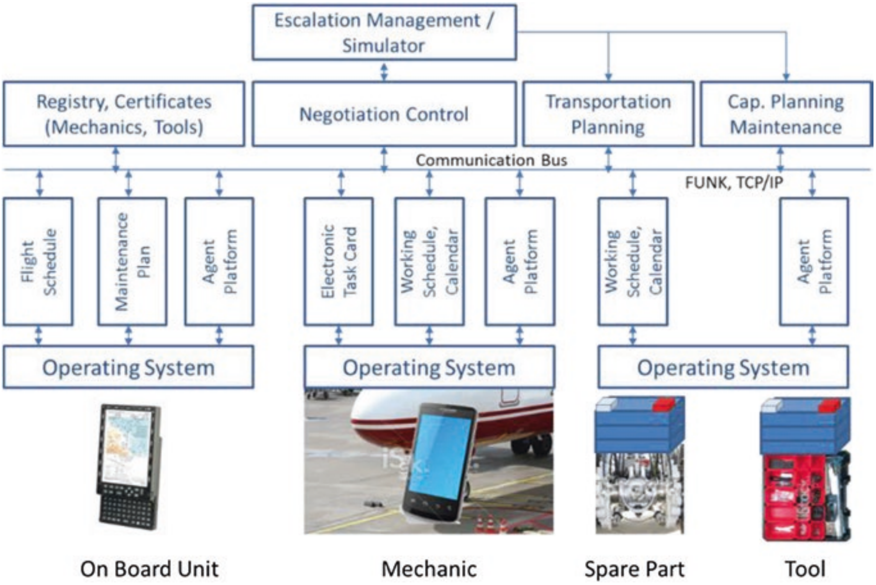

Fig. 2 Execution architecture for CPS based MRO

For instance an airplane on the way from Palma to Basel recognizes a problem and has to take under consideration, that even though the mechanic and the spare part are available in Basel, the expensive tool is not. With the help of decentralized software agents negotiating with each other, a suitable tool in Oslo is identified and processed to a regular line flight from Oslo to Basel. With that the software agents can make sure that the tool is available right in time.

Nevertheless, facing the introduced issues, this first architecture has some disadvantages:

- The strong decentralized communication load between the entities requires a huge amount of infrastructure performance,
- Evident possibility of unauthorized manipulation of each entity CPS,
- High cost for CPS on tools and spare parts because full CPS capability electronic is still very expensive.

4.3 CPS for MRO in Train Transportation: A Second Case Study

The SURFER project led by Bombardier Transport aimed at developing a CPS-based solution for the active and intelligent on-line train monitoring of doors [19]. The proposed architecture is holonic-based, using the features of the holonic principles, namely recursivity (the same active and intelligent monitoring principles apply at a door, vehicle and train levels) and cooperation (information exchange among holons at the same level to avoid false alarms as well as to ensure robust information to be transmitted at upper levels). Information is aggregated and enriched thoroughly the different levels until the maintenance centre to avoid data burst (“small data” instead of “big data”), to reduce reaction times and to provide the maintenance centre with accurate and up to date health status prognostic. SURFER big data treatment works as a CPS, based on the on board and wayside networks, and will allow to the train problem to be an input for the maintenance CPS, by giving continuously an evaluation of the maintenance to be done, from the train “point of view”, see Fig. 3.

From a MRO of a fleet of CTS point of view and facing the introduced issues, this approach is necessary but not sufficient:

- Only the doors which are critical system from a safety point of view have been considered. Other critical sub-systems such as HVAC or bogies must also be considered.
- The integration with the maintenance centre has not been realized. At this step of the development, only information is provided to this centre. There is no feedback to the train, and there is no global optimization of MRO tasks considering maintenance centres, parts and maintenance operators.
- The fleet level was not addressed; the train was the higher addressed level. Obviously, the SURFER project can be seen as the first brick toward the fleet MRO level, the train being seen as a maintenance agent.

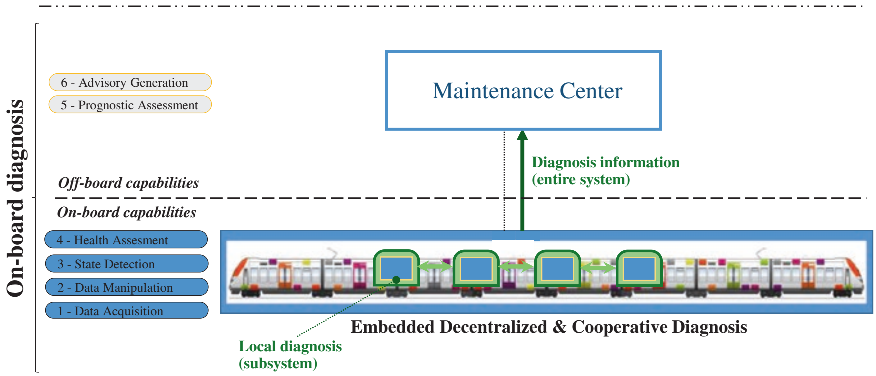

Fig. 3 The SURFER approach

4.4 *Synthesis*

These are two illustrative examples from industrial projects. In fact, CPS are already widely adopted and developed in all transportation sectors but like for these two examples, the potential benefits of full CPS are not really used and CPS are often reduced to “simple” functions such as the ones provided by sensor networks that are being used to acquire, process and forward digitalized information about the ‘health’ status of transportation system components. In this way maintenance and repair can be planned [20], while the management of data, the work assignment for MRO stations and the synchronization with fleet management and transportation routing has still to be manually performed today. The increasing complexity described above in the transportation sector requires more automation and flexibility and the authors think that a step forward must be put to fully adopt the potential benefits of the CPS paradigm. For that purpose, in the next section, a set of complementary specifications to be met to optimize the planning and control of MRO operations of a fleet of CTS using CPS are proposed.

5 Specifying an Advanced CPS for MRO Planning and Control

From the experience gained in these two past industrial projects, the authors intend to design an improved CPS based MRO tasks planning and control system considering the following new innovative components:

- CTS such as train or airplane must be active and intelligent agents able to trigger maintenance needs, even in an opportunistic way, based upon an accurate health status management of their systems (diagnosis and prognostics). They must be able to negotiate maintenance tasks planning and control directly with other CTS of the fleet and with maintenance centres. These tasks must be considered jointly with their logistics (spare parts, operators, tools, maintenance centres).

- A hybrid agent system architecture responsible for the negotiation between the MRO objects, in order to facilitate self-organization, must be designed. In this context *hybrid* means to facilitate centralized and distributed agent negotiation at the same time. *Centralized* means those agents are executed on one platform, just connected to the CPS, having just RFID and possibly sensor capabilities. Distributed peer-to-peer agents are running directly on complete CPS embedded or connected, with all capabilities: computing, storage, RF, sensors. Both do have advantages and disadvantages and especially in the diverse world of transportation systems the support of both approaches is required (especially in the transformation period).
- A high performance middleware must be integrated to realize the massive communication exchange between the different agents operating in the entire MRO planning and control procedures.

For that purpose, the CPS4MRO (CPS for MRO) architecture is proposed and specified in the remaining of this paper. First, this architecture must support a secure access to full intelligent CPS (such as the extended electronic flight bag system in airplanes) as well as to simple CPS, providing location and auto-id data. The handling and negotiation for MRO objects with simple CPSs will be supported by a centralized agent platform, which is connected to a high performance middleware (see Fig. 4). An encapsulated management service platform provides all the background procedures to administrate and configure the negotiation rules as well as to assure the connection to all other required MRO and airline or train service providers operating IT-functions.

This hybrid platform also supports a centralized approach where all agents running on one clustered IT-System include:

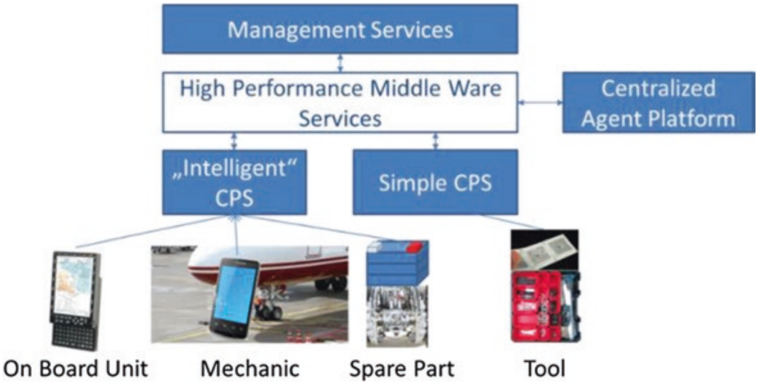

Fig. 4 Helicopter view about system architecture of the proposed CPS4MRO

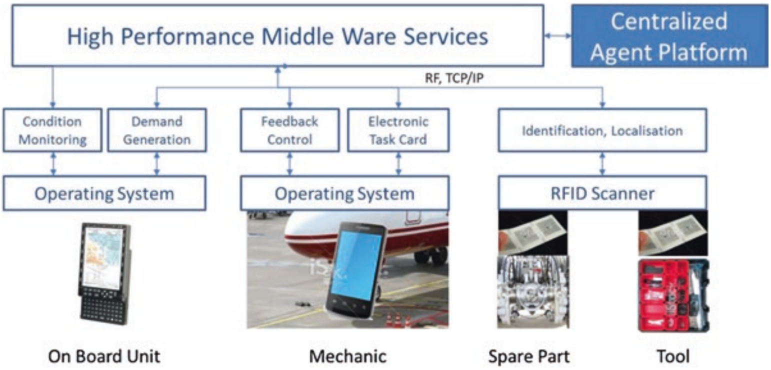

Fig. 5 Simple CPS connected to the hybrid architecture with centralized agent execution

- Higher performance negotiation procedures;
- Reduced complexity and cost on MRO object site.

The middleware services enable simple CPS to connect to the agent platform, see Fig. 5. The equipment for several MRO objects is identical with those of intelligent CPS, but includes some different software functions. The mechanic keeps the electronic task card, but the negotiation between agents will be coordinated by the centralized agent platform.

In order to manage the high volume communication, the high performance middle ware services have to overcome today's typical inefficient data transformation. The current systems offer a homogeneous interface between different applications, independent if they are running completely next to each other or not on the same kernel. An interface definition language (IDL) for servers and clients, which allows transparent access to services by the client in a highly efficient manner, can overcome this situation. The interface definition has to be independent from the actual implementation languages for the individual applications and does not make any assumptions on the distribution of these applications. The applications can use their native data structures for communication and do not need to worry about efficient transformation of the data.

6 Conclusion and Perspectives

In this paper a new architecture named CPS4MRO, that goes a step further previous research development and industry-oriented projects led by the authors, was proposed and specified. The aim is to provide in the near future an optimized planning and control of MRO operations of a fleet of CTS using the paradigm of Cyber-Physical Systems. The authors intend to apply these developments to different transportation fields: fleet of planes, fleet of trains and fleet of trucks.

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Toward an Ontology-Based Architecture for Cloud Manufacturing

Asma Talhi, Jean-Charles Huet, Virginie Fortineau and Samir Lamouri

Abstract In this study we introduce a first step to build a Cloud Manufacturing architecture. Cloud Manufacturing is an emerging paradigm in which dynamically scalable and virtualized resources are provided to the users as services over the Internet. Our architecture will serve as a platform for mapping users and manufacturing resources' providers with the aim of enhancing collaboration within Product Lifecycle Management (PLM) by reducing costs and development time. Since some vendors may use different descriptions of their services we believe that semantic web technologies like ontologies are robust tools for mapping vendors' descriptions and users' requests in order to find the suited service. Our ontology is under development and will include concepts from holons, PLM and Cloud Computing.

Keywords Cloud manufacturing · Ontology · Architecture · HMS

1 Introduction

With the growing need of users for sophisticated products, one of the challenges that the companies face today is to satisfy the customer's request by offering products with best quality at low cost and short development time. To achieve this

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A. Talhi (✉) · V. Fortineau · S. Lamouri
Arts et Métiers, Paris Tech, Paris, France
e-mail: asma.talhi@ensam.eu

V. Fortineau
e-mail: virginie.fortineau@ensam.eu

S. Lamouri
e-mail: samir.lamouri@ensam.eu

J.-C. Huet
EPMI, Cergy, France
e-mail: jc.huet@epmi.fr

A. Talhi
WYSIWYG S.A.S, Cergy, France

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goal, companies establish partnerships with other organizations, benefiting from their skills and infrastructures. This manufacturing pattern, which enables actors involved in the realization of the product to collaborate through the whole lifecycle, is called networked enterprise [1]. Product Lifecycle Management (PLM) is an approach that allows the management of the product's data in such environments. According to Terzi [2] it is an integrated, Information and Communication Technology (ICT) supported approach to the cooperative management of all product related data along the various phases of the product lifecycle. However, the actual systems are not advanced enough to meet the growing needs of PLM. Lack of flexibility [3], scalability and embedded access to manufacturing resources [4] are the main issues pointed out by the state of the art.

Cloud Manufacturing is a new paradigm where all resources and abilities involved in the whole lifecycle -hardware/software- are provided to the users in a pay-as-you-go manner. Based on novel technologies like Service Oriented Architecture (SOA) and Cloud computing, Cloud Manufacturing is an emerging solution where users can request services ranging from product design, manufacturing, testing, management and all other stages of a product life-cycle. The Cloud Manufacturing term was taken as reported in the literature. Although it gives the impression of treating the manufacturing level, theoretically, Cloud Manufacturing covers all phases of lifecycle that are provided as services.

Our main objective is to design a Cloud Manufacturing architecture based on a framework introduced in Sect. 2.1 in order to enhance collaboration within PLM. In this study we present the key elements to reach our objective and further build a platform for mapping users and service providers in order to achieve PLM projects with best delays and costs. Since some vendors may use different descriptions of their services we believe that semantic web technologies like ontologies are robust tools for mapping vendors' descriptions and users' requests in order to find the suited service. We believe that the inference mechanism of ontologies allow to find out the service that best fits the needs of users.

The rest of the paper is organized as follow: Sect. 2 presents a review of the Cloud Manufacturing system conditions and how the holonic concept can be helpful to set up such system. Section 3 explains how the ontology will be used followed by an example to illustrate what we want to achieve.

2 Related Work

2.1 Cloud Manufacturing Architecture

Based on the National Institute of Standard and Technology (NIST) definition of Cloud Computing [5], Xu [4] introduces the Cloud Manufacturing as "a Model for enabling ubiquitous and on-demand access to a shared pool of configurable manufacturing resources (e.g., manufacturing software tools, manufacturing equipment, etc.) that can be rapidly provisioned and released with minimum effort or service provider interactions." Xu [4] distinguishes between two visions of Cloud Manufacturing:

(i) Adopting of some Cloud Computing technologies into the manufacturing environments;
(ii) Cloud Manufacturing as the manufacturing version of Cloud Computing.

In our study, we focus on the second point. A general representation of how a Cloud Manufacturing should be was first introduced by the same author. The Cloud Manufacturing system is based on multi-layer framework that includes:

- *Manufacturing Resource Layer* (MRL): contains the resources needed during the lifecycle;
- *Virtual Service Layer* (VSL): where identified manufacturing resources are virtualized and packaged as a service;
- *Global Service Layer* (GSL): responsible for locating, allocating, and monitoring the manufacturing resources;
- *Application Layer/User Domain* (UD): serves as an interface between the user and manufacturing cloud resources.

A review of the web-based solutions in the literature can be found in [6]. The analysis of the solutions is based on the framework described above and aims to know whether a solution is compliant with Xu and fulfils the four layers. According to this definition, Cloud Manufacturing architecture should be based on a mediator illustrated by the Global Service Layer. The mediator is in the domain of the enterprise that will serve as intermediate entity between the users and the Cloud resources. The aim of this study is to provide the first step to achieve our goal of building such architecture: modelling our domain.

2.2 The Holonic Concept

As the Cloud Manufacturing provides resources needed during the product lifecycle, it includes manufacturing equipment. The question we can ask is how to ensure access to the physical resources or entire factories, via internet. This led us to explore the possibility of doing it thanks to the Holonic Manufacturing concept that aims to make the manufacturing systems more intelligent and agile. Indeed, the increasing complexity of manufacturing systems searching for more flexibility, fault tolerance lead to the development of new models in order to be able to manage these changes efficiently.

The concept "*Holon*" was introduced the first time by Koestler [7]. It's an autonomous entity which has a degree of independence and is a part of a "whole": an environment with which it communicates and cooperates.

A Holonic Manufacturing Systems (HMS) is defined as: "system components of autonomous modules and their distributed control and consists of resource holons, product holons and order holons" [8]. According to the holon's architecture introduced by Bussmann [9] we notice that a holon has a “logical” part that allows the control and the communication with the physical part.

We believe that this definition is suitable for the “manufacturing” part of the Cloud Manufacturing since our aim is to make physical entities interact with other services and remotely accessible.

2.3 Cloud Manufacturing Models

In the literature survey we conducted, no ontology for Cloud Manufacturing that fulfils our expectation exists. The models and ontologies proposed focus mostly on the lower layer of the framework: the “provider layer” in order to model the manufacturing service. Wang et al. [10] propose models based on EXPRESS-G to describe the manufacturing services and its providers. Ameri et al. [11] introduce a methodology for developing manufacturing capability ontologies. Manufacturing capability model in this proposal characterizes a manufacturing facility and its constituting elements including devices, machines, operators, etc. Lin et al. [12] use ontology to model resources of shop floor and Jiang et al. [13] present an ontology-based framework of knowledge integration in networked collaborative manufacturing environment. Our main objective is to define an ontology that will be used by the mediator within the CM platform. As in CM everything is considered as a service, this means that the manufacturing part is considered as a service too, like all the other phases of the lifecycle. For the purpose of this work, we analysed papers that deal with Cloud Computing ontologies and propose solutions from the point of view of a Cloud manager instead of provider. The majority of these studies explain the advantages of using ontologies in Cloud Computing and focus on one feature of this paradigm.

3 Toward an Ontology-Based Architecture

3.1 Why Designing a Cloud Manufacturing Ontology?

The questions we ask are: what will the ontology represent (i) and how will it be used (ii)? We expose below the elements to answer these questions.

(i) The ontology will represent our domain: the cloud manufacturing. The Ontologies are modelling tools that propose a simple and human understandable view of the domain [14] since they represent explicitly the meaning of different terms or concepts with their relationships. An ontology is composed of a set of classes (or concepts) that define the domain. These classes are connected to each other via properties or roles. Axioms (or restrictions) are applied to roles and classes and finally, the ontology is diversified with instances [15]. Indeed, Cloud providers don't use the same "terms" to describe their services. Moscato et al. [16] explain that different Cloud systems and vendors have different ways to describe and invoke their services, to specify requirements and to communicate. Then, there is a need to provide a common access to these services. Kambala et al. [17] argue that "Ontologies have been proposed to solve the problems that arise from using different terminology to refer to the same concept or using the same term to refer to different concepts". Therefore, defining Cloud Manufacturing ontology allows us to overcome this problem, since it represents the common concepts suitable to be used by the different cloud providers that will integrate the CM platform.

(ii) The ontology will be used by a mediator in such way that the latter will be able to discover services in an intelligent and automated way. "Intelligence" here means that the mediator should be able to discover, identify and invoke the right services whatever the definition used to describe them. In addition to that, these services must meet the user's requirements and needs. "Automated" means that the discovery process is executed without manual intervention from the users. However, the two terms are closely linked since automation needs the intelligence to be set up. At this level, we believe that our domain ontology must be an inference ontology to meet these needs. Tsai et al. [18] explain that the reasoning abilities provided by the ontology systems in oriented-service frameworks can facilitate the service matching process, and provide a certain level of flexibility by returning the most compatible services when a perfect match cannot be found, and reduce the manual work for a user.

Figure 1 illustrates the role of the Cloud Manufacturing ontology and its relationship with the mediator. It represents two schemes: the semantic schema represents the mappings between the domain ontology on the cloud providers' description; and the technical schema depicts the use of the domain ontology by the mediator.

3.2 Building of a Cloud Manufacturing Ontology

None of the studies presented in Sect. 2.3 define explicitly the top level concepts a CM ontology. Since the Cloud Manufacturing paradigm encompasses the Cloud Computing, we draw on literature models to build our domain ontology. Indeed, MOSAIC is defined for computing services, while our ontology should model PLM steps as services. In addition to that, modelling the manufacturing physical layer (factories, workshop, etc.) is an important part to be included in the ontology. The holonic concept (Sect. 2.2) is also to be considered in our ontology since it is the solution we believe appropriate for the lower layer. Finally, all these services must be connected to computing services to ensure efficient data transit.

The top level (Fig. 2) is composed of an **Actor** class representing the actors that interact with the Cloud Manufacturing system.

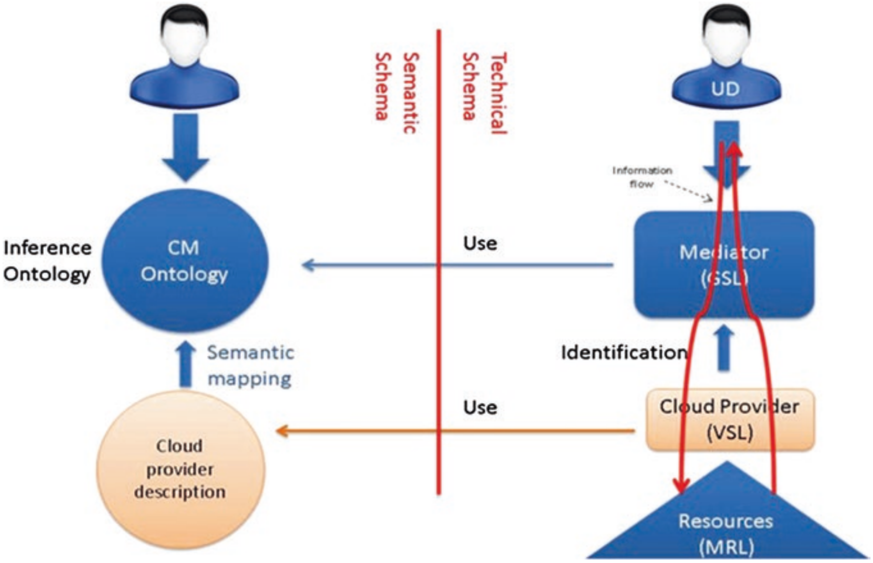

Fig. 1 Relationship between semantic and technical schema

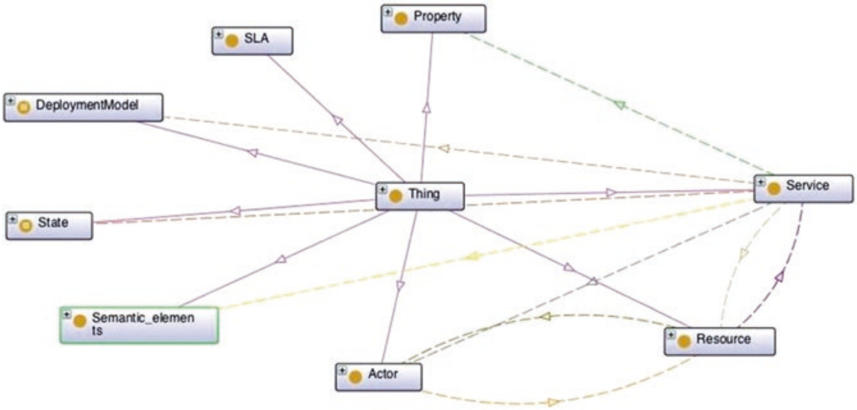

Fig. 2 Top level of CM ontology

The **Deployment Model** class for the Cloud Manufacturing deployment's mode contains the following instances: *Community*, *Hybrid*, *Private* and *Public*. The **Semantic_elements** class contains all the elements needed to allow and facilitate the communication with the service and its use. It consists of: **Data_language**, **Programming_language** and **Protocol.** The **SLA** class includes all the elements needed to define the SLA. The **State** class describes the state of the service and contains the following individuals: free, unavailable, used. The **Property** class is divided into two subclasses: **Functional property** and **Non_functional_property**. The **Functional_property** class describes the elements needed to run a service, whereas the **Non_functional_property** class describes properties that will be considered, in addition to functional ones to decide which service is most suited for a particular user such like **Availability**, **QoS** and **Reliability**.

The **Resource** class describes the resources that will be packaged as service and contains two subclasses: **Hard_resource** combining **Manufacturing_equipment** and **Computational_resources**, and **Soft_resource** that includes non-material resources like **Software**, **Experience** and **Skill**. **Service** is the Cloud system's centric entity. In Cloud Manufacturing all the resources are virtualized and packaged as a service. The **Service** class contains subclasses **PLMaas** and **ServiceModel**. The **PLMaas** class includes PLM phases like: Design as a service (**DaaS**), Manufacturing as a service (**MFGaas**), Simulation as a service (**SIMaas**), etc. The **ServiceModel** class describes the service's categories: **Saas**, **Paas**, **Iaas** and **Holonaas** where the latter is used to describe the service that encompass manufacturing resources.

3.3 Example

Figure 3 illustrates what we concretely want to achieve. Based on his workflow, the user defines the services he needs.

In our example we assume that the user needs a design software and a workshop to manufacture the product. The user should log on to the mediator interface and specify his requirements through a request. The mediator returns the services

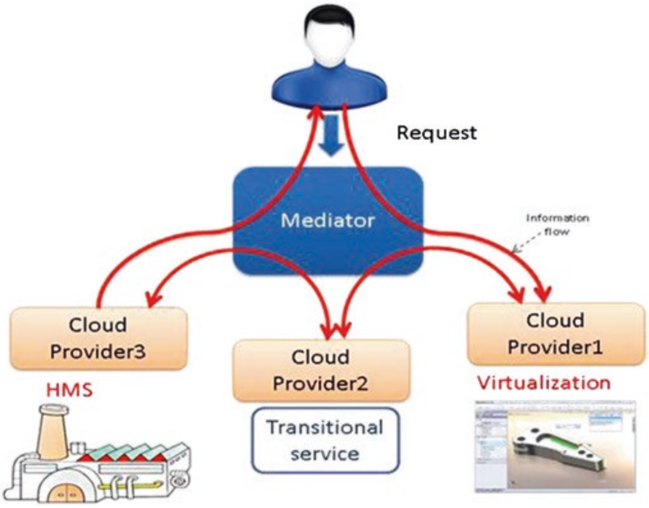

Fig. 3 Example of mediator's behaviour within CM platform

that meet the user requirements. The benefit of defining the ontology is to improve the discovery mechanism of the mediator in order to take in account the semantic aspect of the request and the services' description. In the example, the two services are provided by two different sources which use visualization and HMS respectively to offer access to the resources (software/hardware). To ensure a high level of automation, the mediator should be in charge of interacting with both systems. To establish this communication, the mediator uses the information provided in the description of the services like the input format of data. In this situation, the mediator will call a third service: transitional service, which will handle the format conversion between the design service and the manufacturing service. The Last service is the manufacturing one; it receives product data, processes them and manufactures the product.

4 Conclusion

In this study we presented the first step toward the Cloud Manufacturing architecture: the domain's ontology and the top level of concepts defined within it. The ontology defines the steps of the product lifecycle as services and takes also in account the Cloud computing features (storage, computing capacity, etc.). The production part of the lifecycle is dealt with using the holonic concept which contains a logical part that processes the information and controls the physical resource. The Cloud Manufacturing ontology, although under development, will contribute to intelligent and automated service discovery and will be included in a platform for mapping users and providers.

The next step will focus on the development of the ontology and the mediator that will exploit it. Further researches will focus on methodology that will assist companies in the process of moving toward Cloud manufacturing.

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Part V

Adaptive, Bio-inspired and Self-organized Multi-Agent Systems for Manufacturing

Evaluating the Applicability of Multi-agent Software for Implementing Distributed Industrial Data Management Approaches

Torben Jess, Philip Woodall and Duncan McFarlane

Abstract Distributed approaches to industrial control or information management problems are often tackled using Multi-agent methods. Multi-Agent systems—solutions resulting from taking a Multi-agent based approaches—often come with a certain amount of "overhead" such as communication systems, but can provide a helpful tool with the design and implementation. In this paper, a distributed data management problem is addressed with both a bespoke approach developed specifically for this problem and a more general Multi-agent approach. The two approaches are compared using architecture and software metrics. The software metric results show similar results, although overall the bespoke approach was more appropriate for the particular application examined. The architectural analysis indicates that the main reason for this difference is the communication and computation overhead associated with the agent-based system. It was not within the scope of this study to compare the two approaches under multiple application scenarios.

Keywords Multi-agent systems comparison · Multi-agent systems for data management · Architecture trade-off analysis method · Software metrics

1 Introduction

Over the last 10–20 years distributed approaches have been used for various industrial problems, such as holonic manufacturing. It uses separate distributed entities like machines, or products as representations in the algorithm for finding a good production plan. In contrast to centralized approaches, which are trying to optimize the whole production centrally [1]. Distributed approaches have been shown to be beneficial for various industrial cases such as manufacturing [2]. Often distributed approaches are implemented using Multi-Agent systems [1]. However, there have

T. Jess (✉) · P. Woodall · D. McFarlane
Department of Engineering, University of Cambridge, Cambridge, UK
e-mail: tj282@eng.cam.ac.uk

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also been various cases where alternative approach such as bespoke object-oriented techniques have been used [3]. Multi-Agent systems have the benefit of having some existing techniques to work with such as negotiation mechanism for example. However, they also create a specific overhead costs in the implementation. With the increasing amount of distributed approaches in various domains the problem of selecting a Multi-Agent system for this is approach is therefore becoming more difficult. The question is if it is worth developing a distributed solution using Multi-Agent systems or should alternative approaches be selected?

This paper addresses this question for a data management case. A distributed algorithm has been developed to address the challenge of finding additional relevant data for a supply chain decision problem. We implemented a bespoke solution (specifically designed to implement just this technique using object oriented methods) and a Multi-Agent solution following this distributed algorithm approach. In order to compare both implemented systems, we used architecture evaluation with ATAM and software metrics based on the systems requirements to identify which approach is more suitable. We found that the bespoke solution was more suitable for our scenario due to the high overhead costs and the agent thread management of the Multi-Agent system. Section 2 presents the relevant research background. Section 3 describes the problem, the distributed algorithm and the two-implemented systems. In Sect. 4 the two systems are compared and Sect. 5 presents the conclusion for this paper.

2 Research Background

This chapter looks into Multi-Agent systems as a software approach, alternatives for them, and architecture evaluation and software metrics as our comparison approach.

2.1 Multi-agent Software Approaches

Multi-Agent systems are used in a various industrial applications [4], such as holonic manufacturing [1, 2] or supply chain management [5]. Different methodologies and techniques for Multi-Agent Systems have been developed and researched. This includes different Multi-Agent architectures (such as BDI for example), different methodologies such as GAIA [6], MaSE or PROMOETHEUS and many more [7, 8] for example. An overview about Multi-Agent systems can be found in Wooldridge [9].

2.2 Alternative Software Implementation Approaches

Distributed software approaches can be implemented using all kinds of software approaches. In practice and in research projects the main alternatives are standard object oriented techniques. There are various examples of object oriented holonic manufacturing systems for example [3, 10].

2.3 Approaches to Comparing Software Design and Implementation

This review focuses on the techniques applied in this paper, which are software architecture and software metrics. There exist two types of methods for the evaluation of software architecture, software architecture analysis methods such as ATAM or SAM [11] and performance prediction models such as queuing networks or petri nets [12]. This paper uses ATAM as the general accepted industry standard for software architecture analysis methods. ATAM is relying on a set of scenarios (based the system on requirements) defined by users and stakeholders. These scenarios are analyzed using simple prototypes or “back of the envelope” approximation, and combined in a utility tree [11]. ATAM is a qualitative method but showed good results in industrial examples [13, 14]. For software engineering metrics comparison software engineering has intensively studied the field of software system comparison. Various works have addressed different aspects of the evaluation for example bug detection [15]. Various papers provide a good overview about the large number of measures [16, 17]. There have been measures for different aspects of the software system like costs or programming time [18, 19]. This paper is mainly concerned about identifying suitable measures to technical evaluate an implemented software system.

3 An Industrial Data Management Problem, Solution and Implementation Approaches

3.1 The Industrial Data Management Problem

Currently users in procurement have a lot of effort in finding the relevant data within different databases and also have the risk of potentially missing parts of this information. For example a supply chain user might have to order life vests. He does not know about all the other orders of life vests from his company (previous and current orders) and cannot use this information to get a discount. The goal of this system is to this information gap within a company by giving the user the additional data required. Searching for the data is not always an option since the user is not always aware of its existence.

3.2 A Distributed Solution for the Industrial Data Management Problem

The solution to this problem automatically identifies interesting data for the user. Instead of having a centralized approach going through the data to identify similarities our approach uses a distributed technique in which each data item can find related data items and connect with them. In order to do this each data item (in our case a row) goes through different databases and looks for other data items with similar syntax to itself. This way whenever a specific row is presented to the user the other joined rows can be presented as well.

3.3 Implementation of the Distributed Solution Approach

A bespoke and a Multi-Agent Systems approach were identified as possible architectures for the problem. Both are using the same underlying techniques and therefore also have the same overall results for the user. In the implementation of both systems we used similar coding styles to avoid any potential bias in the evaluation.

3.3.1 Bespoke Implementation

The bespoke system has DataWrappers as its main concept. The DataWrapper represents a piece of information and are compared to other DataWrappers. When the user asks for additional information the DataWrapper x of the information the user currently sees (e.g. an order of life vests) compares itself to a list of candidate DataWrappers generated by a DataWrapperManager. These candidates are compared to the presented DataWrapper x representing the life vests. If the comparison value is above a certain threshold then a Join (in this case Join a between two orders of life vests) between the two DataWrappers (x and n in the figure representing two orders of life vests) is created. Once all Joins are generated the best connections are presented to the user (in this case Join a).

A diagram of the architecture can be found in Fig. 1.

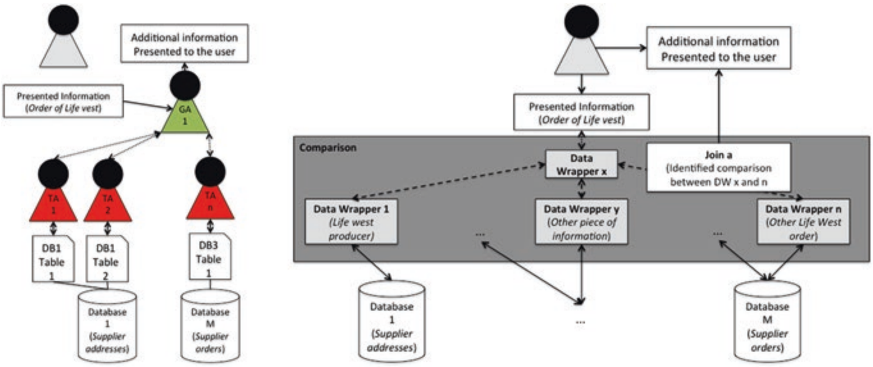

Fig. 1 Description of the multi-agent system (*left*) and the bespoke solution (*right*)

3.3.2 Multi-agent Implementation

The Multi-Agent architecture is build around two types of agents GUIAgents and TableAgents. The GUIAgent is used to answer to the requests of the user and forward these requests to the TableAgents (see Fig. 1). He interacts with the GUI presented to the user and tries to present additional information to the user. When the user requires additional information the TableAgent (e.g. order of life vests) receives the message from the GUIAgent requesting similar information to be send to the TableAgent. TableAgents represent a database table and its content. He has access to the data from the table.

He compares its own information against the information currently presented to the user (using the same comparison criteria that the bespoke system is using) and replies with the information he thinks are relevant for the user.

4 Evaluation of Software Design and Implementation

This section compares the two systems using ATAM and software metrics.

4.1 ATAM Evaluation

The architecture evaluation followed the 9 ATAM [11] steps except for minor changes due to limited stakeholder availability and a small number of developers: In Step 1 and 2 (Present ATAM and Present business driver) the ATAM process and the relevant business drivers were introduced to all developer and stakeholder (see Kazman et al. [11] for details on ATAM and Sect. 3.1 for the business drivers). In Step 3 and 4 (Present architecture and Identify architectural approaches) was done using the two architectural approaches (see Sect. 3.3). In Step 5 (Generate quality attribute utility tree) a list of scenarios for the evaluation was generated by brainstorming [11]. Three main categories performance, availability, modifiability and implementation were identified. The scenarios were then ranked by importance (see Table 1 for details). In Step 6 (Analyze architectural approaches) the different scenarios are evaluated using ATAM techniques such as short prototyping or back of the envelope analysis [11]. Both architectures were ranked based on their results in this analysis from 1 (very easy to fulfill scenario requirements with this architecture) to 5 (very difficult to fulfill scenario requirement with this architecture) for each scenario (see results in Table 1). Step 7 and 8 (Brainstorm and prioritize scenarios and analyze architectural approaches) are mainly a verification in testing step within ATAM [11]. We used the advantage of having a small group of developers and stakeholders and already incorporated stakeholder feedback in Step 5. In Step 9 (Present results) the results of the report where gathered and presented.

Table 1 ATAM evaluation (*I* Importance [*3* high, *2* Medium, *1* Low]), *Ag*. Agent and *Bes*. bespoke is the rank and the rank times importance (in parentheses) for each architecture

ID	Description	Approach	I	Ag.	Bes.
Performance					
P1	Time for the system to respond to user in demo of approx. 30 S for 2 databases	Sequence breakdown with simple prototypes for time estimate with main computation steps	3	3(9)	4(12)
P2	One additional relevant piece of information for every supply chain task found	Depends on syntactic matching algorithm which has potential to deliver additional information based on initial tests	3	2(6)	2(6)
P3	Work with 10 databases and in 20 S with same accuracy	Use analysis from P1 and adjust time for larger sizes	1	1(1)	2(2)
Modifiability					
M1	Experienced developer can include additional tables within 15 min of effort	Analyze architecture to number of places were this change would occur	1	5(5)	5(5)
M2	Background programming can easily be implemented	(See M1)	1	5(5)	3(3)
M3	Semantic matching can be incorporate by changes to 1 method	(See M1)	2	5(10)	5(10)
M4	Tables can be accessed dynamically	(See M1)	1	5(5)	3(3)
Availability					
A1	Risk of system to fail during a short demonstration is below 1 %	Assume failure probabilities for major units and use as basis for whole system failure estimate	3	5(15)	5(15)
A2	Risk of database connection failure at the start is below 1 %	(See above for failure probability of major units)	3	5(15)	5(15)
Implementation					
I1	The system can easily be implemented by a single developer within 2 weeks	Breakdown the different sequences and estimate effort involved in implementing them	3	3(9)	5(15)
Total				80	86

4.2 Software Metrics Comparison

Both systems were evaluated on the measure in Table 2; selected based on, first their ability to address the criteria: performance, modifiability, availability and implementation, second their measurability with existing tools, and third based on how established they are within the software engineering/metrics community [16–19]. For performance we relied on requirement specific time measures and were looking at two values. The first was performance of existing functionality, looking at the switching between different orders as a measure for existing system time performance. As a second measure we used the time for each system to

Table 2 Software metric comparison results for both architectures (multi-agent and bespoke)

	Bespoke	Multi-agent
Performance		
Average time to find additional data and present it in a separate GUI	225.4 ms (STDEV: 131.5)	484 ms (STDEV: 195.2)
Switching between different cases	30.9 ms (STDEV: 12.8)	41.6 ms (STDEV: 6.2)
Modifiability and implementation		
Lines of code	1,637	1,896
Number of methods	161	156
Number of operations	492	639
Decision count	107	130
Number of classes	23	29
McCabe cyclomatic complexity	1.639 avg over all classes	1.808 avg over all classes
Lack of cohesion	0.481	0.378
Coupling factor	0.096838	0.0591133
Halsted program length [20]	5,130	5,946
Halsted program difficulty [20]	78	81.21
Halsted Time to program [20]	58 h	72 h
Halsted delivered Bugs [20]	16.11	19
Availability		
Number of failures during runtime	0	0

find additional data. The evaluation was done on a three databases. Database 1 is a parts system containing 2007 part details. Database 2 is an HR system containing 32,924 employee entries. Database 3 is a procurement system containing our test cases with 4 orders and 3 items.

4.3 Analyses and Interpretation of Results

We used the criteria: Performance, modifiability, availability, and implementation as a structure for our evaluation. The bespoke system shows better performance having twice the speed of the Multi-Agent system for finding data. ATAM and the high standard deviation in response time indicate the reason is table agents being busy with their different behaviors, so they take more time to answer. In addition the workload is distributed differently among TableManagers. One TableManagerAgent requires more time to answer and check its content then others. However JADE allocates each agent similar time intervals, so some TableAgents block others with their regular behaviors. For modifiability and implementation the Multi-Agent architecture had slightly worse results due to higher measures in complexity and size of the code. However the difference in measures is only small, indicating similar complexity for modifiability and implementations. This is consistent with the ATAM analysis. Both architectures perform well for availability due to the low risks of underlying systems like databases failing. The architecture analysis indicates that a bigger likelihood of underlying system failure would show higher benefits of the agent system.

5 Conclusion

This paper analyzed whether an agent-based approach can help within the implementation of a specific distributed data management algorithm. We implemented two systems: an agent-based and a bespoke solution. They were compared using ATAM architecture evaluation and software metrics. Our results indicate that the bespoke solution is more suitable for the project and its requirements; mainly due to the agent approach being slower and having a higher implementation/maintenance effort. The reasons are the delay based on the thread management for all agents and the problem of misallocation of processing time by distributing time equally to all agents independent of workload within JADE.

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Self-interested Service-Oriented Agents Based on Trust and QoS for Dynamic Reconfiguration

Nelson Rodrigues, Paulo Leitão and Eugénio Oliveira

Abstract Progressively increasing complexity of dynamic environments, in which services and applications are demanded by potential clients, requires a high level of reconfiguration of the offer to better match that ever changing demand. In particular, the dynamic change of the client's needs, leading to higher exigency, may require a smart and flexible automatic composition of more elementary services. By leveraging the service-oriented architectures and multi-agent system benefits, the paper proposes a method to explore the flexibility of the decision support for the services' reconfiguration based on several pillars, such as trust, reputation and QoS models, which allows the selection based on measuring the expected performance of the agents. Preliminary experimental results, extracted from a real case scenario, allow highlighting the benefits of the proposed distributed and flexible solution to balance the workload of service providers in a simple and fast manner. The proposed solution includes the agents' intelligent decision-making capability to dynamically and autonomously change services selection on the fly, towards more trustworthy services with better quality when unexpected events happen, e.g. broken machines. We then propose the use of competitive self-interested agents to provide services that best suits to the client through dynamic service composition.

N. Rodrigues (✉) · P. Leitão · E. Oliveira
LIACC—Artificial Intelligence and Computer Science Laboratory,
Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
e-mail: nrodrigues@ipb.pt

P. Leitão
e-mail: pleitao@ipb.pt

E. Oliveira
e-mail: eco@fe.up.pt

N. Rodrigues · P. Leitão
Polytechnic Institute of Bragança, Campus Sta Apolónia, 5301-857 Bragança, Portugal

E. Oliveira
Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

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1 Introduction

The manufacturing industry is facing self-organization and evolution, the implementation of shop floor flexibility and reconfiguration being regarded as some of the many global challenges of the upcoming decade [1]. The literature is full of good examples regarding the benefits of the Service-Oriented Architecture (SOA), seen as an excellent solution to face the many current industry challenges, namely providing interoperability in heterogeneous systems and adaptability to condition changes, allowing companies to save time and money by simplifying the execution of complex tasks to be carried out. As a consequence, a big effort is being developed to embed intelligence and autonomy in the services' discovery, aggregation and composition processes, which can be achieved by using Multi-agent Systems (MAS) combined with SOA [2]. In addition, the dynamic and automatic reconfiguration of the distributed system, e.g., by adapting or creating new services offered by the several autonomous agents to face the new identified requirements, needs to be studied. Self-organization in MAS is being explored aiming to achieve, in dynamic and open environments, more trustworthy and automatic reconfiguration services. Assuring modular capabilities, a system is composed of components that are organized in a variety of configurations, flexible enough to execute different services and intelligent to reconfigure the services in an automatic manner [3].

This paper proposes a model to design and evaluate, at run-time, several service composition hypotheses, allowing selecting the best proposals that will support the agent's self-organization and the improvement of its utility. The proposed hypothesis increases the service composition quality by appropriately selecting the best service providers based on several non-functional requirements (e.g. service performance, cost, availability, besides the response time), usually referred as Quality of Service (QoS) [4]. The agent's ability to interact and choose the best services is based on certain Key Performance Indicators (KPI) that express the confidence in the services' providers, such as quality, reputation and trust. In a competitive mode, the agents adjust their own KPIs to improve the possibility to become credible candidates for selection, increasing the utility of each client agent. The proposed concepts were applied to a case study and the preliminary results show how important may be the dynamic service allocation through competitive agents, allowing scheduling a production plan by balancing the task effort.

The rest of the paper is organized as follows: Sect. 2 presents the literature review and Sect. 3 introduces the proposed model. Section 4 describes the experimental case study and performs a critical analysis of the achieved results. Finally, Sect. 5 wraps up the paper by stating the conclusions.

2 Literature Review

The importance given to the selection of the optimal services has been widely studied in the literature [5], being strongly related to the selection of services in a centralized repository. Initially, this selection process was carried out in a manual manner, but lately, some efforts are driven to automating the discovery and composition phases. The optimum process composition, considering the optimization of the workflow composition by QoS features, is not new [6]. The nature of workflows design is devoted by complex systems concepts, where MAS represents a suitable paradigm to implement and facilitate such complexity, by subdividing the problem space in a distributed, flexible and autonomous manner. Some authors analyse the flexible workflow topics [6, 7], proposing methodologies to coordinate the workflows and raising also the service-oriented computing to support inter-organizational workflows. Buhler and Vidal refer that, theoretically, such adaptation should appear regarding the monitoring of self-* properties [8], but the authors do not provide details on the trigger learning module. Mendes et al. [9] propose the service composition in the industrial domain, formal specified by Petri Nets models, however no learning mechanisms are explored. Our work takes into consideration the recent proposal of Vogel and Giese [10] that propose a model-driven for self-adaption based on feedback loops and the selection of the most promising agent [11]. Essentially, there is a lack of implementing approaches regarding self-organization features that consider distributed MAS [3] selecting the entity that provides the best service. In fact, the literature review does not offer expressive enough detail and results in the creation of such systems. This lack of detail offers a research opportunity to adapt self-interested agents, based on self-organization to actively re-configure service's features on the fly, improving the composition concerned.

3 Proposed Approach

In emergent and volatile environments, systems need to quickly adapt to changes or unexpected disruptions [12], e.g. changes in operating conditions or product demands.

3.1 Combining Multi-agent Systems and Service-Orientation

To deal with this kind of scenarios, the proposed architecture combines MAS and SOA paradigms to support an easy decentralization and distribution of decision-making entities, allowing that autonomous and self-* agents adapt dynamically and in a distributed manner their behaviours in due time (see Fig. 1). The SOA principles provide several features, such as standardized service contracts, loose coupling,

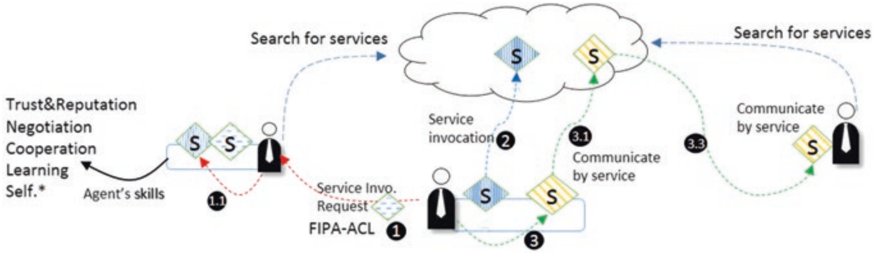

Fig. 1 Combining the interoperability of SOA and the intelligence and autonomy by MAS

service abstraction and service reusability, among others, allowing designing complex systems based on the offer and consumption of those services, each one encapsulating the functionalities of an intelligent system or agent. The agents communicate among themselves using FIPA-ACL messages to request a service execution (1), or by invoking directly the service (2), or lastly, by invoking a service that encapsulates others services (3). In this way, services provided by the agents can be consumed.

Each agent has the skills (e.g., trust mechanisms or learning) that by default are not publicly exposed. Depending on the competitiveness or cooperation of the agents system, some skills are mapped as services and others left as private. In the proposed MAS, the following agents were included:

- *Provider agent* (PA) having the capability to provide one or more services that can be performed and correspond to its skills. The PA is autonomous to dynamically change the offered services as well as the associated conditions, e.g., price and QoS, and tries to offer its services to be used as much as possible, inside its own limitations.
- *Consumer agent* (CA) corresponding to the entity that requests a service that is required to execute its workflow. The CA is autonomous to decide which service best suits its particular needs. During the negotiation with the PAs, the CA aims to increase its utility, choosing the service needed with lower price and higher trust, reputation and QoS value by default. Moreover, each CA has an internal database to collect the feedback knowledge about the QoS, trust, and prices about several services of a specific PA.
- *Discover agent* (DA) providing self-discovering mechanisms that are required to find potential services relevant to the consumer, i.e. the agent can reason of the services' skills (e.g. trying to create possible coalitions between services).
- *Workflow agent* (WA) having the responsibility to monitor the quality of the available services and to dynamically create the best composition of services. For this purpose, CA interact with the WA expecting to receive the best composed planning scenarios, which are ranked by the quality, price and reliability of the composition within the consumer constraints.
- *Ontology agent* (OntA) having the capability to clarify possible misunderstandings during the agents' interaction for the negotiation and cooperation processes, e.g. applying semantic-based mechanisms to translate concepts.

- *Reputation* agent (RA) and *observer agent* (OA) work in a centralized manner by gathering the results of the services' execution, being able to provide advising based on their expertise. The RA collects a feedback value after each executed service and the OA collects the information after the execution of each process plan. These agents support their decisions based on prediction algorithms working upon the past events.

Each agent is autonomous, being able to choose which task to perform, e.g. an agent may refuse the execution of a service if it perceives that a service will jeopardize its internal functionality. The agent's roles also allow the system to dynamically self-organize to evolve with more confidence becoming more robust.

3.2 Service Selection Mechanisms

The analysis of the performance of PAs by CA agents must consider several KPI and thus, a multi-criteria function formalized by a Multi-Attribute Utility Theory (MAUT) to maximize the agent's utility is used. From the several possible criteria to evaluate possible partners for a business agreement, the trust, reputation, QoS and price (with different weights) were selected. Furthermore, it is important to specify the attributes that are associated with the services and agents. In Table 1 service variables were built based on both the models presented in [4] for QoS,

Table 1 Representation of the agent and services variables

Name and equation	Description	Actors
QoS availability $f(\phi) = \frac{\sum\lambda}{\sum\lambda + \sum\psi} * 100$	Ratio of the service uptime of time period, λ standing for service uptime and ψ for the service down time	Service
QoS response time $f(\theta) = \delta - \rho$	Performance of a service. Given by the difference between conclusion time δ, and ρ the request time	Service
QoS throughput $f(\eta) = \frac{\sum\gamma}{\sum t}$	Provider performance index. Given by the maximum number of services to process in a unit of time where γ stands for the complete request and τ for the unit time	Service
QoS processing time	Cost associated to an execution time	Service
Price	Cost function	Service
Trust Trt(Xtr, Ytr, Cxt, G, t)	Trust value of the agent in performing a specific service, where *Xtr* represents the trustor, *Yte* means the trustee (the one under assessment), in a context *Cxt*, for a specific goal *G* at the time *t*	Agent
Reputation Rp(Tp, Xtr, Yte, Cxt, G, t)	Trust value of the agent, where tp = {tp1, …, tpk} is a set of recommendations, given by a third-party recommender Tp about a trustor agent Xtr	Agent

and Jonker and Treur [13] for the trust model. Trust and reputation are important criteria to measure the confidence and the risk that may be implicit in a future bilateral contract.

Moreover, and according to each specific situation, the weights of the different criteria can be customized. For example, if the client prefers a reliable product with higher quality than the cheaper product, then the WA agent must select the best services based on trust and QoS. From the PA side, the goal is always to increase its utility, by selecting the best strategy to maximize the revenue.

The PA agent that sooner recognizes the needs of consumers, early adapts to eventually be the selected provider. This competitive and adaptive approach allows to dynamically scheduling the tasks without using a complex scheduling algorithm, allowing at the same time to balance the task efforts for each producer. However, this heuristic-based methodology raises relevant questions: how to discover opportunities to adapt and how, at the same time, should be the dynamic selection of composed services performed. Each agent must explore the opportunities to adapt, e.g., when the agent is not performing any service or when the agent's utility is changing, particularly having a decreasing trend. These are possible opportunities considered in the case study.

4 Case Study

Aiming to validate the work, the proposed approach was implemented for the flexible manufacturing system "AIP PRIMECA" [14], which is composed of several stations connected through conveyors. Each station performs a set of operations (i.e. services) but only one single operation at a time. The catalogue of products comprises several distinct products, namely "B", "E", "L", "T", "A", "I" and "P", each one containing a production plan (workflow) that defines the sequence of operations for each product. For example, the production of the product "B" requires the execution of the *Plate_Loading* service, three times the *Axis* service, twice the *r_comp* service, followed by the sequence *l_comp*, *Screw_comp* and *Inspection* services and finally the *Product_unloading* service. These services can be performed in different stations; however, each station has different performances (see [14] for further analysis).

4.1 Case Study Agentification

The agent-based model for the production system case study was implemented using JADE (Java Agent Development Framework) [15]. In particular, the behaviours of PA, CA, DA, RA, WA and OA agents were implemented according to the proposed architecture, as well the interaction patterns among these agents.

Regarding the implementation phase, a scenario with two different batches of products was considered:

- #a: 2 batches of “BELT” products (comprising the “B”, “E”, “L”, “T” sub-products), totalizing the execution of eight products.
- #b: 1 batch of products “AIP” (comprising “A”, “I”, “P”), totalizing the execution of 3 products.

The system starts by initializing 7 PA to represent the stations disposed in the production system, 1 OA to supervise the production system activities, 1 RA, 1 OntA and finally, 11 CA agents, one for each product instance. To simplify the case study, only one criterion, i.e. the price, will be shown for evaluating the producer’s proposals.

4.2 Analysis of the Experimental Results

The case study production system is sufficiently flexible for the agents to extract the benefits of it, e.g. the same service can be offered by several PAs with different features, e.g. Machine2 and Machine3 are PA agents that provide the service *r_comp*.

The experimental tests consider a simulated dataset running in static and dynamic environments. In the first round, the utility of agents follows a static behaviour in relation to the price, e.g. PAs never change the price of a particular service. In the second round, the prices were dynamically adjusted according to the profit. Figure 2 depicts the difference of PA utilities for the first and second round. In the first round, the Machine2 PA had executed the *r_comp* service with a utility of 8 units (i.e. an indication of the cost) during 50 iterations (see left graph of Fig. 2). At this time, Machine3 PA was only able to perform the *Axis* service. In the second round, the Machine3 PA has changed the service’s characteristics of the service *r_comp,* which has increased its utility (in this case changing only the price; see right graph of Fig. 2).

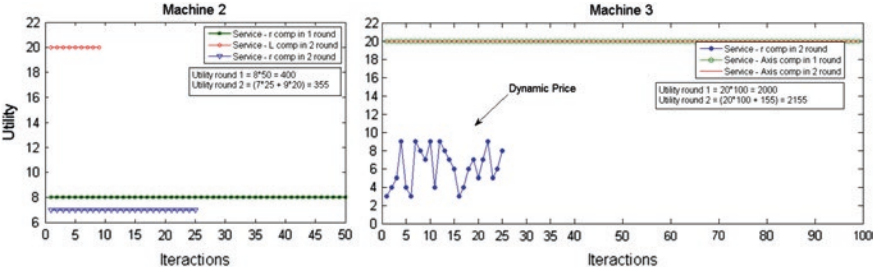

Fig. 2 Utility of services provided by Machine2 and Machine3

Table 2 Achieved Cmax using fixed or dynamic plans with/without perturbations

Scenario	Cmax (m:s) x = Trust (0.2) y = QoS(0.3)		Cmax (m:s) x = Trust (0.4) y = QoS(0.1)	
	Fixed	Dynamic	Fixed	Dynamic
Without perturbations	32:23	33:26	32:31	32:50
With perturbations	47:26	45:48	45:41	45:21

The reason for the dynamic behaviour in the Machine3 PA, illustrated in the right graph of Fig. 2, is related to the fact that sometimes the service *r_comp* is sold too cheap and the PA agent pretends to increase its utility, thus increasing the price. But in other hand, sometimes the price of *r_comp* service offered by Machine3 PA is set too high and consequently is not being sold (being instead selected the service offered by the Machine2 PA). Again, to increase its utility the Machine3 PA has to reduce the price, and consequently, this competitive behaviour offers opportunities for other PA agents to perform services. CA agents can choose the provider of the services, instead of a rigid plan, allowing the increase of the utility of the services and agents in the second round. The PA can observe and identify strategies being carried on in the environment, being capable to explore any market-based strategies.

During the simulation, the criterion to be optimized was Cmax, representing the amount of time necessary to complete a group of jobs. The weights for the multi-criteria function used in the service selection are: 0.3 for the *price*, 0.2 for the *Rep*, *x* for the *Trust* and *y* for QoS (see *x* and *y* values in Table 2). The experimental tests also considered the existence of perturbations, e.g. delays in the process execution, which will provoke a lack of fulfilling the commitment agreed in the negotiation (accordingly, the CA considers the failure of the commitment as a negative reward of a particular provider). The achieved results are illustrated in minutes and seconds in Table 2.

Analysing the impact of the multi-attribute function with a trust weight of 0.2 and without perturbations, the fixed approaches achieve a lower Cmax, which is expected since there are no errors and the plan is executed without deviations. In the dynamic approach, the achieved Cmax is considerably higher for each negotiation protocol, being more prominent when the production batch is bigger. Obviously, in the scenarios with the presence of perturbations, the Cmax is higher. Additionally, it can be realized that the fixed approach in the presence of perturbations has higher Cmax values than the dynamic one, due to the flexibility provided by the dynamic approach to detect, in a pro-active manner, that a station has some kind of perturbation, and adapt properly.

The same tendencies were achieved using a trust value of 0.4. Note that PA agents with better confidence do not guarantee that the service has higher quality. In some cases, the Cmax is higher if the confidence increases too much. Thus, the agent's capabilities to select and evaluate the correct providers infer the final product quality.

5 Conclusions

The progressively increasing complexity of dynamic environments, in which services and applications are demanded by potential clients, requires a high level of reconfiguration of the offer to better match that ever changing demand. To address this challenge, a service-oriented multi-agent system approach was proposed, to intelligently and dynamically select the most appropriate services provided by the reliable entities to increase the confidence and quality of the needed service composition. This paper explores the challenges of selecting services considering self-adaption capabilities, in order to improve the services availability and quality. The heuristic-based game played by the agents for the services selection based on trust, reputation, QoS and price, allows balancing the workload of the providers in a simple and fast manner. The proposed self-oriented agent-based system was applied to a simple production system case study aiming to validate its applicability. The achieved results lead to the conclusion that the system performance was improved along the following lines:

(i) Reducing the impact (down-times) of broken processes.
(ii) Reacting faster and accurately to condition changes, offering products with higher quality and without spending time implementing a dedicate schedule function.

In conclusion, the results convinced us to extend our approach to other domains, namely considering a distributed reputation model, and negotiation strategies to improve the system's intelligent decision capability.

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Volatile Knowledge to Improve the Self-adaptation of Autonomous Shuttles in Flexible Job Shop Manufacturing System

Emmanuel Adam, Damien Trentesaux and René Mandiau

Abstract It is well known now that MAS are particularly adapted to deal with distributed and dynamic environment. The management of business workflow, data flow or flexible job shop manufacturing systems is typically a good application field for them. This kind of application requires flexibility to face with changes on the network. In the context of FMS, where products and resources entities can be seen as active, this paper presents an application of the volatile knowledge concept to the management of a flexible assembly cell. We illustrate our proposition on an emulator of the flexible assembly cell in our university.

Keywords Volatile knowledge · Flexible job shop manufacturing systems · Multi-agent system

1 Introduction

To be competitive, manufacturing industries adapt to changing conditions imposed by the market. The greater variety of products, the possible large fluctuations in demand, the shorter lifecycle of products expressed by a higher dynamics of new products, and the increased customer expectations in terms of quality and delivery time are challenges that manufacturing companies have to deal with to remain competitive.

E. Adam (✉) · D. Trentesaux · R. Mandiau
LAMIH Lab., UMR CNRS 8201, UVHC, 59313 Valenciennes, France
e-mail: emmanuel.adam@univ-valenciennes.fr

D. Trentesaux
e-mail: damien.trentesaux@univ-valenciennes.fr

R. Mandiau
e-mail: rene.mandiau@univ-valenciennes.fr

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In recent decades, scientific developments in the field of production have defined new architectures including the hierarchical/non-hierarchical architectures that play a prominent role in FMS.

Several bio-inspired approaches have been- and are proposed. Some of them are based on stigmergy, like for example, the Ant colony optimization (ACO) [5] and the Firefly Algorithm [12]. Others are based on Particle Swarm Optimization (PSO) [7], like Bee Based Algorithms [10] (Bee Colony Optimization, Honey Bee Colony Algorithm, a.o.), Roach Infestation Optimization (RIO) [6].

In this paper we propose an alternate solution to the use of a shared environment and of a control layer (we have already proposed approaches using Potential Fields and a holonic architecture [1]) for the management of dynamic and mobile entities that evolve on a unidirectional routing graph, and that can be concurrent (like conveyors of a flexible job shop manufacturing system).

Our objective is to propose a solution implementable only on the mobile and decisional entities, without the necessity to computerize all the elements of the graph (i.e. the nodes, the edge) and using an acceptable number of messages exchanged between these entities.

So, we took inspiration from the stigmergy to propose the notion of *volatile knowledge*. That means that rather than depositing pheromones which degrade themselves in a shared environment, the agents (the shuttles) communicate between them knowledge to which they degrade the confidence level; when knowledge has a too low level of confidence, it is removed. The advantage of this solution over existing bio-inspired approaches is that the control is totally distributed among the 'intelligent' (mobile and/or decisional) devices: there is no need to use a centralized and common layer that would manage the signals deposited by the agents in the environment. Another advantage is that the solution is directly implemented inside the active devices; it is not a centralized solution computed by a main controller that assigns the tasks to the mobile agents.

Such a "*forgetting*" *of information* has already been used in order to improve the learning times of Reinforcement Learning in [13]. In fact the notion of forgetting has been studied since years in the context of classical logic (it also known as variable elimination) [9]. In this paper, we focus essentially on the forgetting of observations.

The paper presents the notion of volatile knowledge dedicated to the management of a flexible job shop manufacturing system. An experimentation of this concept using a benchmark dedicated to manufacturing cell management is then presented in the third section.

2 Volatile Knowledge for Flexible Assembly Cells Management

In [2, 8], we have proposed the concept of volatile knowledge adapted to the management of communication between autonomous vehicles that evolve on a unidirectional routing graph (a road being composed of two opposite unidirectional lines).

We apply in this paper this concept to the management of a flexible job shop manufacturing system; this new application leads us to improve the previous model of volatile knowledge.

We give here some elements of definition of volatile knowledge, which we illustrate through an application for the management of a flexible assembly cell.

A flexible job shop manufacturing system contains assembly cells. In this paper, we consider a flexible assembly cell, like described in [11], which is composed of autonomous shuttles that receive orders to execute products. A product is composed of different parts, is placed and assembled on a shuttle, checked once it is complete and removed. Theses tasks (add a component, deposit, check, remove) are done by workstations distributed in the cell. Each workstation is able to provide one or more services, which cannot be shared at the same time. Also, the paths between workstations are limited to the use of only one shuttle and are unidirectional. The shuttles try to find the best workstations to create the products, i.e. the workstations providing the desired service in a minimum of time. To do that, the shuttles can decide at each cross point which path they will use.

In our approach, a shuttle informs the other shuttles about its intention (the next workstation at which it plans to move), and about events (like fault/repairing of a workstation). So, two types of knowledge are used: reservation of a workstation, and fault/repairing of a workstation.

2.1 Elements of Volatile Knowledge Model

A knowledge is a partial view of the environment or of the other agents, namely for a given object *o* of the environment (the traffic network for example); it is (generally) an incomplete copy of it, so a representation of *o* with missing attributes and methods.

We define knowledge k_o^a (cf. Def. 1) on an object *o* for an agent *a* by: $o_{a'}$, a partial view of *o* from *a*; $date_{ko}$, the date when the knowledge has been created or updated (by *a* or by another agent if the knowledge has been received); $builderAgent_{ko}$, the 'builder' of the knowledge (name of the agent that has created/updated the knowledge from its perception); $senderAgent_{ko}$, the 'sender' of the knowledge (name of the agent that could have sent the knowledge to *a*); $conf_{ko} \in [0,1]$ the confidence that *a* has on k_{ao}; $deg_{ko} \in [0,1]$ the percentage of confidence degradation applied at each 'step'; $threshold_{ko} \in [0,1]$ the threshold under which the knowledge is no more considered (and has to be removed); $shareable_{ko}$, the fact that the knowledge is shareable or not by *a*.

$$\mathrm{k}_o^a = \begin{pmatrix} o'_a, date_{\mathrm{k}_o^a}, builder_{\mathrm{k}_o^a}, senderAgent_{\mathrm{k}_o^a}, \\ conf_{\mathrm{k}_o^a}, deg_{\mathrm{k}_o^a}, threshold_{\mathrm{k}_o^a}, shareable_{\mathrm{k}_o^a} \end{pmatrix} \tag{1}$$

Confidence and volatility: In a dynamic environment, it is necessary to allow automatic update and cleaning of the out-dated or invalidated beliefs.

In our model, at each step, each passage in the life cycle of an agent (perception-cognition-action) or at each 'tick' given by a simulator, the confidence on knowledge is degraded[1]:

$$conf_{\mathrm{k}_o^a} \leftarrow conf_{\mathrm{k}_o^a} \times \left(1 - deg_{\mathrm{k}_o^a}\right)$$

Knowledge k_o^a can be perennial ($deg_{\mathrm{k}_o^a} = 0$) or volatile ($deg_{\mathrm{k}_o^a} > 0$) (we note $\overline{\mathrm{k}_{o\,0}^a}$ a perennial knowledge). For an agent a, the first knowledge received, perceived or given about an object is considered as perennial; for example, a shuttle agent (mobile agent) starts with the manufacturing cell map, knowing the length of the roads between the resources, i.e. the weights of the edges. All the other knowledge relative to the same object will be considered by 'a' as volatile.

If $\left(\overline{k_{o0}^a}, k_{o\,1}^a, \ldots, k_{on}^a\right)$ is a list of knowledge that a owns on an object o, we consider that the first knowledge, $\overline{k_{o0}^a}$, is perennial: $deg_{\overline{k_{o0}^a}} = 0$.

Initially, $conf_{\overline{k_{o0}^a}} = 1$, but when volatile knowledge about o are added, this confidence is degraded; we propose that: $conf_{\overline{k_{o0}^a}} = 1 - max\left(conf_{\overline{k_{oi}^a}}\right)$.

If more than one knowledge exists relatively to a same object, it is necessary to normalize the confidence values: let L be the sum of the confidences of the knowledge that owns a about the object o, $L = \left(\sum_{i=0}^{n} conf_{k_{oi}^a}\right)$, for each confidence, we have: $conf_{k_{oi}^a} \leftarrow \frac{conf_{k_{oi}^a}}{L}$.

Example

let agent 'a' be an agent whose knowledge at a given time about an object 'ob' are (k_0, k_1), with $conf_{k1} = 0.4$, that implies that $conf_{k0} = 0.6$.

Next, 'a' received a new knowledge about 'ob' (k_1), with $conf_{k2} = 0.7$. That implies firstly that $conf_{k0} = 0.3$, and next, with the normalisation, that $conf_{k0} \approx 0.2$, $conf_{k1} \approx 0.3$, $conf_{k2} \approx 0.5$.

When 'a' receives an information with a confidence of 90 % which it stores in k_3, the confidences are modified so that: $conf_{k0} \approx 0.05$, $conf_{k1} \approx 0.2$, $conf_{k2} \approx 0.3$ and $conf_{k2} \approx 0.45$.

Figure 1 represents the distribution of the confidences.

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[1] Or if $conf_{\mathrm{k}_o^a}^{\mathrm{t}_0}$ is the confidence at $time = 0$, confidence $conf_{\mathrm{k}_o^a}^{\mathrm{t}_n} = conf_{\mathrm{k}_o^a}^{\mathrm{t}_0} \times \left(1 - deg_{\mathrm{k}_o^a}\right)^n$.

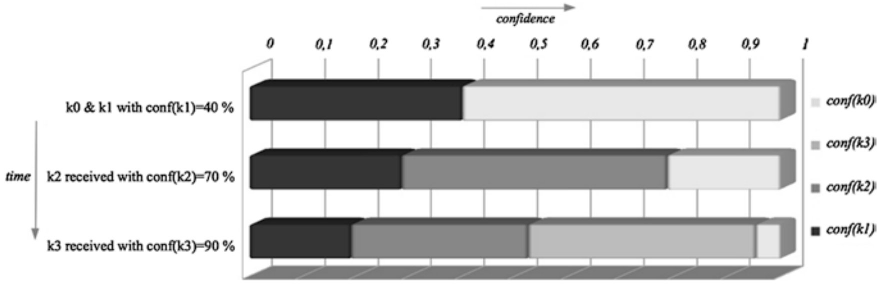

Fig. 1 Example of storage of knowledge relative to a same object

2.2 *Aggregation of Knowledge*

It occurs that different knowledge about a same object coexist in the belief of an agent *a*. Depending of the type of knowledge, we use different ways to select or aggregate the knowledge.

Frequent changes of state: When the knowledge reflects a dynamic and frequent change of an object state, the agent *a* uses a fitness proportionate selection (i.e. roulette wheel selection) to choose which knowledge and which value of an object will be taken into account to evaluate a strategy.

Example
information about the load of the road/rail '*r*' between two workstations, i.e. the actual speed allowed on '*r*' due to some traffic-jam, is an information prone to frequent evolution. It is not conceivable for a mobile agent to be fully trustful with the last information sent by another agent. The probability to take into account knowledge is, in this case, equal to the confidence on the knowledge.
In the Fig. 2 the agent selects the knowledge k^a_{r2} and plans its actions considering that the speed limit on the rail is 0.65 m/s.

Fig. 2 Example of roulette wheel selection of knowledge

Rare but important changes of state: When the knowledge is relative to an important change of state of an object *o* that happens rarely but has a huge impact on the system performance, the agent *a* selects the surest knowledge (that is generally the most recent knowledge about *o*).

Example

a workstation failure has a huge impact on the manufacturing cell performance; when an agent has to take a decision, as long as it considers that a workstation could be defective, it considers this one as effectively faulty and takes a decision with this information. In Fig. 3 the agent selects the knowledge k^a_{r3} that is the more probable and plans its actions considering that the workstation '*w*' has a failure.

Use of a resource: When the knowledge is relative to the use or the future use of a resource, the agent '*a*' adds-up the knowledge relative to this resource.

Example

when a shuttle agent '*a*' plans to use a workstation, it sends to the other agents its destination and the time it will use the resource, with a confident on the knowledge computed so that the knowledge will be forgotten when it ('*a*') will leave the resource. A shuttle agent '*b*' adds up all this kind of information, which can be considered as reservation, to compute how much time the resource is taken up by the other shuttle agents.

In Fig. 4, the agent knows that the duration for a process on the workstation '*w*' is 10 s (it is its first and so perennial knowledge about '*w*', $\overline{k^a_{fw0}}$), and that three other agents are using or planed to use '*w*' (respectively for 20, 40 and 30 s). If nbProcessings is the number of processings that the agent has to make on '*w*', the total duration for using '*w*' is the sum: $20 + 40 + 30 + \text{nbProcessings} \times 10$.

Fig. 3 Example of selection of the most probable knowledge

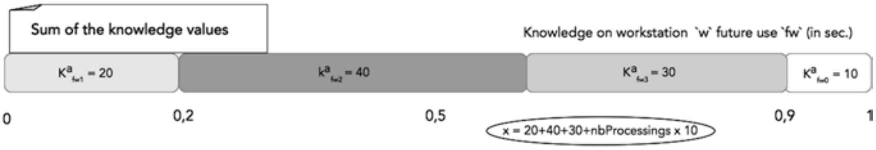

Fig. 4 Example of sum of knowledge

2.3 Confidence Evolution

As stated previously, all the knowledge, except the perennial knowledge, decreases at each step its confidence: $conf_{\mathrm{k}_o^a} \leftarrow conf_{\mathrm{k}_o^a} \times \left(1 - deg_{\mathrm{k}_o^a}\right)$.

As long as the degradation coefficient is dependent of the knowledge nature (perennial or volatile), it depends also of the knowledge object.

Example
knowledge relative to a rail/road load would have a greater degradation coefficient than the knowledge relative to a fault on a workstation. And knowledge relative to the workstation occupancy should be stored in the knowledge only as long as this occupancy is true.

When the confidence on knowledge goes under the threshold, the knowledge is removed from the list of current knowledge and put in a list of 'doubtful' knowledge. Figure 5 presents an example of confidence degradation of volatile knowledge with a low coefficient of degradation.

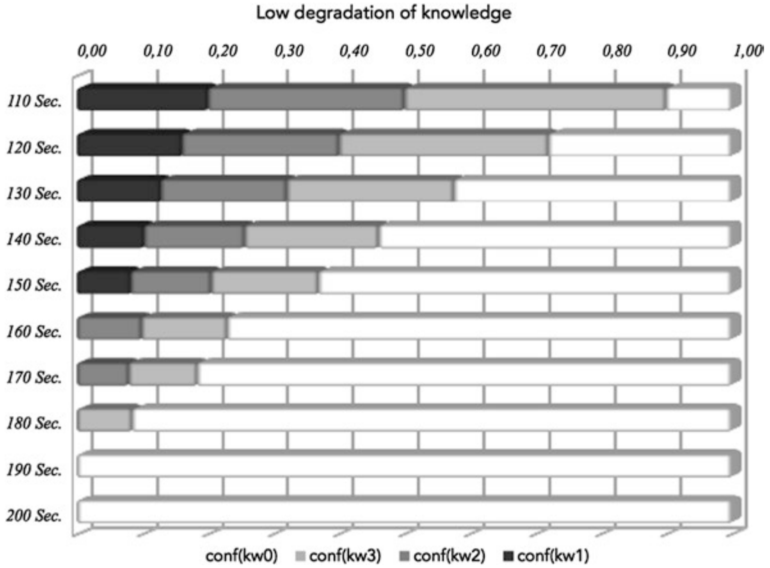

Fig. 5 Examples of knowledge forgetting

A doubtful knowledge is restored and put back in the list of current knowledge if the agent perceived directly that its information is correct, or if it receives a more recent version of the same information from another agent 'b' ($date_{k_o^b} > date_{k_o^a}$).

When an agent perceives or receives an information similar to one in its knowledge list or in its list of 'doubtful' knowledge, the confidence is restored if needed (if the new confidence perceived $conf^{t}_{k_o^a}$ is 'significantly' different than the computed confidence $conf^{t'}_{k_o^a}$), and the degradation coefficient is adapted.

This principle of knowledge management is dedicated to agents evolving in a dynamic environment, subject to modifications; it allows an agent to take into account different observations about a same object in order to take a decision. During an action, the agent is able to check if an information is still valid or not, and to modify its knowledge list consequently.

3 Applications of Volatile Knowledge: Flexible Job Shop Problem

We have applied our model on different applications, like traffic road simulation, management of autonomous vehicles and flexible manufacturing cells management. In this paper, we give a brief description of these last applications.

In order to evaluate the volatile knowledge approach proposed in this paper, we use a case study inspired from the benchmark proposed in [11].

This benchmark considers jobs to be processed on different machines. Each job has its own production sequence composed of some elementary manufacturing operations. Those operations or tasks can be executed on one or more machines. A machine can perform different types of operations. The assignment of operations to the machines is not a priori fixed like in the traditional job shop problem. Most of the flexible job shop problems are proved to be NP-hard [4]. The flexibility increases significantly the complexity of the problem because it requires an additional level of decisions (i.e., the selection of machines on which the jobs should be processed) [3].

3.1 AIP: A Real Flexible Manufacturing Cell

The benchmark is based on a real flexible manufacturing cell located in our University. Seven machines are connected using a transportation system, which is a one-direction monorail system with rotating transfer gates at routing nodes. Thus, this transportation system can be considered as a directed, strongly connected graph, where shuttle move to build the products.

Figure 6 represents the AIP manufacturing cell; nodes n_1, …, n_{11} are decisional nodes where a shuttle can decide the next node to reach; the orientation of the small nodes can not be changed. For example, on the node n_2, a shuttle can decide to go to machine M_1 or to node n_3. By existing from the node M_1, the shuttle is directed toward the node n_3.

The machines M_1, …, M_7 are also nodes where the shuttles can stop to do some processing on the product they have to build. There are 8 different processing tasks which can be performed by the machines: load a plate, place an axis, place a component that represents an ‘r’, or an ‘L’ or an ‘I’, place a screw, inspect the product, and unload the pallet on which the product has been fixed. Some machine can do several processing tasks (e.g., machine M_2 can either put an axis, an ‘r’ component or an ‘L’ component). The numbers in Fig. 6 correspond to the number of time units needed to perform a particular job. In the case study proposed in this article, machines M_6 and M_7 are not used.

Assembling a product consists of combining elements that represent shapes of letters. From the product specifications at AIP, it is possible to build the letters: ‘A’, ‘b’, ‘E’, ‘I’, ‘L’, ‘T’ and ‘P’. From these jobs, it is possible to build products like ‘bELT’, ‘AIP’, ‘LATE’. Figure 7 presents the components and the different jobs created from these ones (a view of the real AIP is presented in [11]).

Each product starts by a plate loading and concludes with an inspection and a plate unloading. Table 1 gives the details of the jobs between these steps, for each letter (*N.B.* if the product ‘T’ and ‘P’ have the same sequence of jobs, the components are not assembled in a same way).

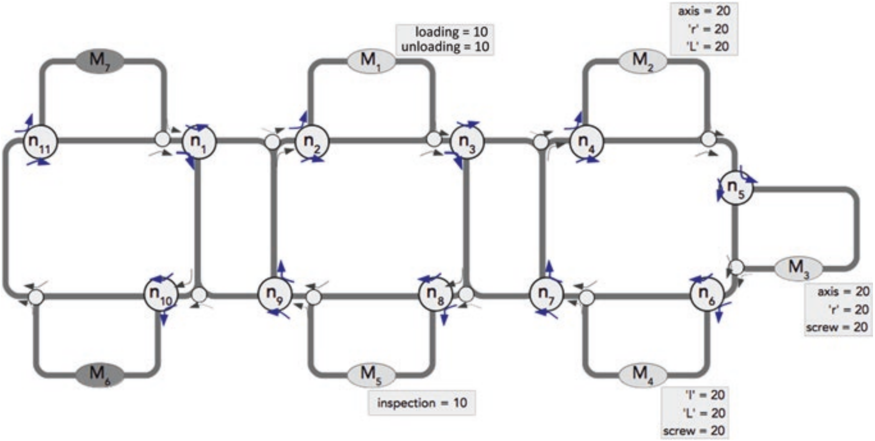

Fig. 6 Schema of the flexible assembly cell

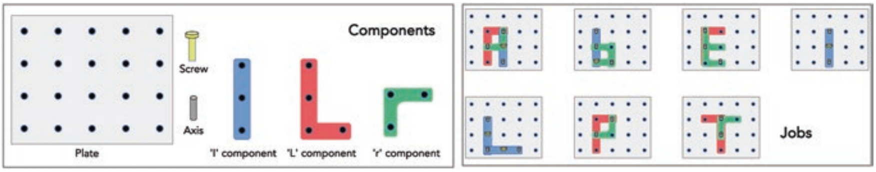

Fig. 7 Schema of the components and jobs used in the AIP cell

Table 1 Sequence of jobs (except load, inspect and unload) by letter

Letter	No. of jobs	Jobs sequence
A	10	3 × axis + 1 × r + 1 × L + 1 × I + 1 × screw
b	10	3 × axis + 2 × r + 1 × I + 1 × screw
E	9	3 × axis + 2 × r + 1 × L + 1 × screw
I	7	2 × axis + 1 × I + 1 × screw
L	10	3 × axis + 2 × I + 2 × screw
T	7	2 × axis + 1 × r + 1 × L
P	7	3 × axis + 1 × r + 1 × L

3.2 Experimentations

In order to implement the concept of volatile knowledge, a simulator has been developed with the JADE platform.[2]

The map of the AIP has been drawn with the JOSM tool and was used as an oriented graph. At the beginning of the simulation, and each time a shuttle has to assemble a new product, the shuttle creates the list of the different strategies (the list of different resources/machines sequence) that will be used to create the product (to perform the list of jobs). Each strategy is evaluated (by the length of the path it describes and the estimated time required to do the described jobs), and the agent chooses the best strategy after each job, of when the shuttle receives knowledge relative to a modification of the AIP components (rails, resources).

Scenario without fault: Several scenarios have been tested; we focus here on the scenario ‘I0#3’ from the benchmark. In this scenario, 3 shuttles have to build a product ‘bELT’ (so each of these shuttles has to do the sequence of jobs ‘b’, ‘E’, ‘L’ and ‘T’), 2 shuttles have to build a product ‘AIP’ and 3 shuttles have to build a product ‘LATE’. This scenario involves 8 shuttles, and allows evaluating the efficiency of the approach based on volatile knowledge.

The ‘time’, in fact the number of ‘ticks/steps’ used by a shuttle in our simulator to build a ‘bELT’, a ‘AIP’ and a ‘LATE’ are respectively of 1,451, 1,068 and 1,477 steps. The, the scenario ‘I0\#3’ has been evaluated:

(a) Without any cooperation and communication between the shuttles;
(b) With communication of local information about a resource only when arriving on this resource;
(c) With communication to the others of the next objective (the next future use of a resource);
(d) With ‘full cooperation’, i.e. with communication of next objectives and of information about resources.

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[2] A Java Agent Development framework, cf. http://jade.tilab.com/.

Eight shuttles (s_1, …, s_8) are 'launched' sequentially; s_1, s_4, s_7 have to build each a product 'bELT', s_2, s_5 are each dedicated to a product 'AIP', and shuttles s_1, s_3, s_8 have to execute each one a product 'LATE'.

Table 2 gives some details on the experimentations. The communication of local information and of future use of a resource improves the total time needed to execute all the products; **the full cooperation allows an improvement of ≈17 % for the total time** and the longest task, and of ≈24 % for the shortest task. Thus, with cooperation, the conflicts concerning resources occupancy are avoided, or at least limited: a shuttle selects the workstation corresponding to its next task that has the lowest occupancy rate (at the date it planned to use it).

Dynamic scenario: The main objective is to allow to the shuttle to adapt to dynamic events like: rush orders, breakdowns, order cancellation, a.o. In [11], 15 scenarios of events occurring in a dynamic production system have been detailed. In this paper we use the dynamic scenario '*#PS4*': "*At a given time, the machine processing time increases for all its operations in a given time window.*" So a shuttle has to avoid, if possible, the use of this resource and use another one if this is more beneficial.

In this scenario, machine M_2 is modified from *step* = 100 to *step* = 1,000, all its processing times increase from 20 *steps* to 200 *steps*. Table 3 describes the new number of steps for scenario 'I0#3' after adding a fault on machine M_2. Without cooperation, with the fault, the total time is ≈54 % greater than in normal case. With cooperation, the total time with perturbation is ≈32 % greater than in normal case, if the degradation coefficient related to knowledge about perturbation is too high. With a smaller degradation coefficient, the information about the incident stays longer in the agents' memory, allowing them not going back to the faulty machine; thus the total time with perturbation is only ≈25 % greater than in normal case. *The cooperation allows minimizing the impact of a fault of* 50 % *relatively to an egocentric behaviour.*

Table 2 Time (in no. of steps) to build the products of the scenario 'I0#3'

Product	Shuttle	(a) No Coop	(b) Local Info	(c) Next Obj	(d) Coop
bELT	s1	2,105	1,511	1,619	1,814
AIP	s2	1,498	1,326	1,418	1,131
LATE	s3	2,406	2,016	2,038	1,921
bELT	s4	2,280	2,102	2,131	2,026
AIP	s5	1,731	1,178	1,397	1,326
LATE	s6	2,017	2,002	1,793	1,767
bELT	s7	2,491	1,973	1,989	2,040
LATE	s8	2,195	2,321	2,082	1,796
	Total	**16,723**	14,429	14,467	**13,821**
	Max	**2,491**	2,321	2,131	**2,040**
	Min	**1,498**	1,178	1,397	**1,131**

Table 3 Time (in no. of steps) following a fault on the machine M_2

	No cooperation		Cooperation		Coop. low degradation	
	Fault	Malus/no fault (%)	Fault	Malus/no fault (%)	Fault	Malus/no fault (%)
Total	25,848	**54.5**	18,320	32.5	17,342	**25.4**
Max	3,704	**48.7**	2,669	31	2,774	**36**
Min	2,338	**56**	1,835	62.2	1,338	**18.3**

4 Conclusion

In order to allow the propagation of knowledge between mobile agents in a dynamic environment, a model of volatile knowledge has been presented.

This simple model allows representing different types of knowledge used to manage flexible assembly cells. It allows also to propagate knowledge about perturbations and to return to normal situation in a distributed way without coordinator. It could be considered as a stigmergic approach that does not use a shared environment. Thus, our proposal can be applied in most of the assembly cells where the shuttles or the products are 'intelligent' enough to manage and communicate information with other products.

In the results presented in this paper, we made the assumption that all agents are cooperative and no defective, i.e. that they cannot send wrong knowledge (the case of a sensor having a dysfunction).

The trust on knowledge depends only on the date from which the knowledge has been updated or created. We plan to introduce the notion of trust that depends on the sender; for example, if an agent perceives that an object has a different value than that in which it had confidence at 90 %, it increases the suspicious potential of the agent that sent it this wrong knowledge. When this suspicious potential reaches a threshold, the agent is considered suspect and the communication with it is disregarded or is considered with a low level of confidence.

Another perspective that we foresee is to use the MILP defined in [11] in the scenario that we use with the Jade simulator in order to compare the efficiency of our approach with the optimal solution.

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A Model for Manufacturing Scheduling Optimization Through Learning Intelligent Products

Wassim Bouazza, Yves Sallez, Nassima Aissani and Bouziane Beldjilali

Abstract The needs of flexibility, agility and adaptation capabilities for modern manufacturing systems increase constantly. In this paper, we propose an original approach combining active/intelligent product architecture with learning mechanism to assure flexibility and agility to the overall manufacturing system. Using learning approaches as Reinforcement Learning (RL) mechanism, an active product can be able to reuse learned experiences to enhance its decisional performances. A contextualization method is proposed to improve the decision making of the product for scheduling tasks. The approach is then applied to a case study using a multi-agent simulation platform.

Keywords Intelligent product · Multi-agent system · Manufacturing system · Learning machine · Scheduling

1 Introduction

Nowadays, for a wide range of products from food and drugs to consumer products, medical devices and automobiles, product problems are magnified in terms of scope and scale within today's global economy consumer [1]. The needs of

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W. Bouazza (✉) · N. Aissani · B. Beldjilali
LIO, University of Oran, 1526 El Mnaouer, Oran, Algeria
e-mail: w.bouazza@gmail.com

N. Aissani
e-mail: nassima.aissani@yahoo.fr

B. Beldjilali
e-mail: bouzianeBeldjilalli@yahoo.fr

Y. Sallez
TEMPO Research Center, UVHC, 59313 Valenciennes, France
e-mail: yves.sallez@univ-valenciennes.fr

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flexibility, agility and adaptation capabilities for the modern manufacturing systems increase constantly.

In this context, this paper aims to demonstrate the interest of extending the active/intelligent product concept with learning capacities. Our work has led us to consider the opportunity provided by the conjunction of two realities.

First, during the last decade, the increasing growth of embedded technologies (e.g., RFID, WIFI or NFC) and the research works in the field of Internet of Things (IoT) have allowed the development of intelligent or "active" products (IP), able to interact with their environment during their total lifecycle [2, 3].

Second, the development of approaches (neural computing, machine learning, knowledge-based systems and expert systems) derived from research into artificial intelligence allows the increase of productivity and quality in FMS [4].

In this paper, after presenting our motivations, a short survey on learning technics in the field of active/intelligent products is provided. In Sect. 3, our approach coupling IP and RL capacities is presented in a context of scheduling in manufacturing systems. The model associated to the IP and the learning technics used are successively described. The Sect. 4 is dedicated to the presentation of the applicative case study, of the used simulation platform and of the first simulation results. Finally, the Sect. 5 offers conclusion and prospective research works.

2 Motivation

In a manufacturing context, if centralized or hierarchical approaches provide long-term optimization of production planning and scheduling, they do not offer the necessary reactivity and flexibility to face perturbations. Recently, some research works [3, 5–7] present IP as a solution to bring the required reactivity. Providing a complete survey on the topic of active/intelligent product is beyond the scope of this paper, but the interested reader can refer to the surveys [3, 5].

Globally, control architectures exploiting active/intelligent products appear appropriate to eliminate or at least reduce the impact of perturbation. However some limitation, called "myopic behaviour", must be noticed [8]. Due to the limited visibility of the IPs on the future behaviour of the manufacturing systems, an optimal performance of the overall system is not assured [9]. To face myopic behaviour [4], the paper presents a dynamic architecture for the optimized and reactive control of flexible manufacturing scheduling, using an holonic architecture.

In our opinion, another interesting way is to exploit the experience of the products via learning mechanisms. Indeed, in some industries like food or pharmaceutical industries, the product encounters similar cases during its life cycle. Using learning approaches as RL mechanism, an IP can be able to reuse experiences to enhance its decisional performances. If RL methods are used in manufacturing systems [10–12], they are rarely coupled with control approaches based on IPs. In fact, if memorization, communication and decisional capacities are often associated to an IP according its level of “activeness”, learning capabilities are more rarely considered. In some typologies, this characteristic is still considered:

- Le Moigne [13] distinguishes seven levels of intelligence, from the object totally passive (such as raw material) to the object able of self-completion. The objects in the upper levels exhibit cognitive capabilities, although the concept of self-finalized object seems a bit futuristic.
- In [7], the intelligent products of level 4 are able to develop their own knowledge to make decisions.

However, in the previous typologies, if learning capabilities are cited, no concrete example is clearly provided.

Moreover, at the best of our knowledge, very few works associate learning capabilities to active/intelligent products. In [14], the authors use a routing approach to find efficient routing paths for active/intelligent products in flexible manufacturing systems (FMS) undergoing perturbations. The stigmergic routing approach uses a technique of reinforcement learning, which allows finding the best path by exploiting the routing experiences of the IPs crossing the FMS. In [15], the authors explore which existent IPs support the measuring, storage, and communication of knowledge based on state-characteristics and process parameters within a collaborative manufacturing environment.

In the next section, we propose a model of IP exploiting a learning function to find the best resolution method for a job shop scheduling problem.

3 Proposed Approach

The present study explores the possibilities to increase the decision capability of an IP in a product-driven manufacturing context, by adding learning mechanism using contextual information.

3.1 Model of the Product-Driven Manufacturing System

In the on-study product-driven manufacturing system, IPs are considered as immersed in their environment and must make decisions based on the current state of the manufacturing context. For the modelling, two main entities are considered:

- *The resources*: Workshops within factories are still generally organized by grouping the same skills of the production means (workstations, machine tools…). They are considered as providers of services (SP) such as: assembly, inspection, etc.
- *The active/intelligent products*: The physical products are considered controlled by a software entity, defining together an IP. The IP is assumed to belong to a

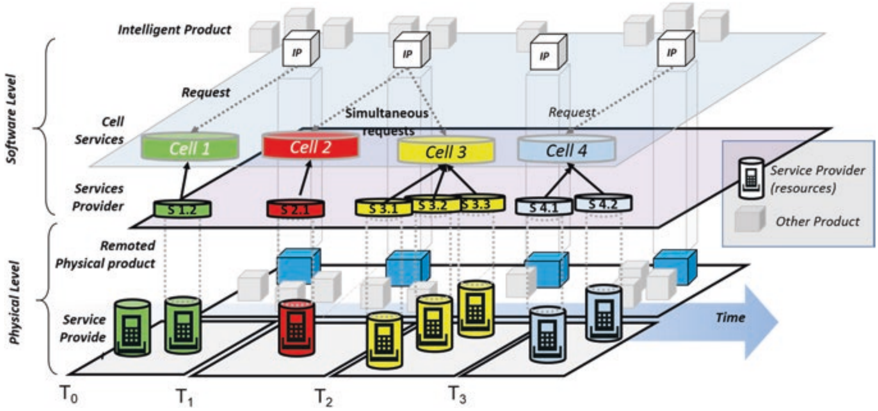

Fig. 1 Manufacturing system based on cells of services providers

product class. A class of products is used to group several products of the same type in a single category which have same specifications. At each product class (e.g. drugs classes in pharmaceutical industry or gasoil type in petroleum's industry), a specific processing time is associated.

As shown in Fig. 1, two levels are considered: a "physical" level composed of the different cells and physical products, and a "software" level. This last contains the computational entities of the resources and of the IPs. According its manufacturing process, each IP requests services from providers at specific times.

3.2 Spirit of the Proposed Approach to Solve Scheduling Problem

One of the most important problems encountered in manufacturing is the scheduling of the production task. The present study explores the possibilities to solve this problem by increasing the decision capability of an IP.

A learning mechanism associated to an IP allows to learn first, and then to reuse this experience in same contextual situations. For example in Fig. 1, the two situations at T_0 and T_3 can be considered as being similar: same number and type of products and same cell configuration. The IP can then reuse the experience learned in T_0 to decide in situation at time T_3.

For this problem, a RL is proposed by adding a concept called "contextualization". This makes possible to show similarity between an actual state and anterior learned situations. This abstraction is made considering four indicators: the *flexibility* of the cell, the *set-up time* needed to start performing the task, the *homogeneity* of the operating times and the *delay* allowed to solve the problem. A context is defined as a system description at instant t. The goal of the RL algorithm is

Table 1 State parameters description

	F (flexibility)			C (setup time)		O (operating time)		D (delay)		
Values	0	1	2	0	1	0	1	0	1	2
Significations	Full	Partial	Dedicated	Without	With	Homogenous	Heterogeneous	High	Normal	Small

to infer a functional relation between the contextual scheduling data and an efficient behaviour of IP. In the next section, this decisional process will be described.

3.3 Decisional Process

The resolution consists to a rule selection considering the contextual parameters (see Table 1). A Q-learning algorithm is adapted to the problem specificities and a target function score is included as a reward. The IP has to choose the adequate dispatching rule (DR) to provide an efficient result to a complex target function (Fig. 2). The specification of the learned function is its capability of predicting the most suitable behaviour for contextualized identified situation.

The decisional process is a Markov decision process based on three elements: States s which is the system description, action a—what to do in that state, and Reward function $R(s, a)$—a decision evaluation. State vector $s(F, C, O, D)$ is defined with contextual data described in Table 1.

According to the state of the system at *time t,* action with the best target function satisfaction is picked. Actions are "choice of dispatching rule", so the IP can promote a final global scheduling to another using the chosen dispatching rule.

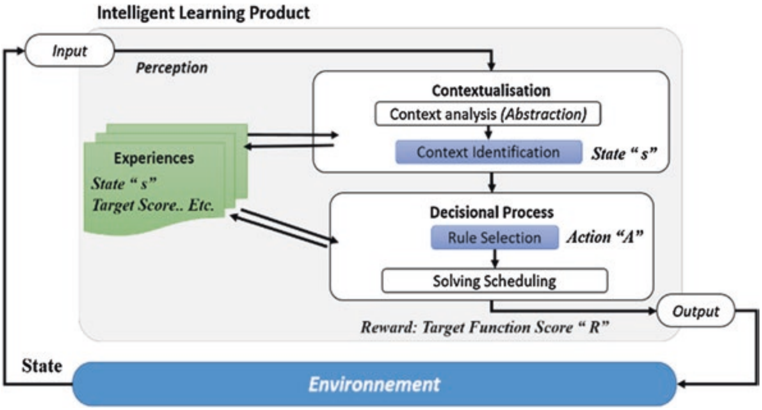

Fig. 2 Simplified representation of the decisional process of the IP

The Reward $R(s, a)$ function denoted $f(x, m)$ is used to calculate the target function corresponding to the sequence defined for a given SP_m for scheduling a given IP_x. For a sequence of size K we have:

$$f(x, m) = \sum_{i=1}^{k} ((\alpha * tg(x, m)) + (\beta * tm(x, m))) \tag{1}$$

α and β are coefficients for weighting: α for the impact of the overall execution time, and β the average execution time. Each agent evaluates then selects the best scheduling.

$$tm(x, m) = Pr(n) * \left(\sum_{i=1}^{k} \left(\frac{Tpa(i, x)}{k} \right) \right) \tag{2}$$

$$tg(x, m) = \sum_{i=1}^{k} (Tpa(i, x)) \tag{3}$$

- $Tpa(i,x)$ is the time to perform a product's task i on a SPx.
- $tm(x,m)$ is the average execution time of products (all tasks) for a sequence k on the SP_m weighted by the priority noted $Pr(n)$.
- $tg(x,m)$ corresponds to the performing time of all k products' tasks of the sequence on a specified SP_m.

For a cell of SPs, many cases must be considered. The same homogenous task's operating time can be provided for all classes. Or, it can vary due to the SP specification, like for e.g. in case of various running process available to perform a same task.

The Q-Learning algorithm was proposed to optimize solutions considering past decisions. At each step of time, an IP observes the vector of state S, then chooses and applies an action a. The goal of the training is to find the sequential order of actions which maximizes the sum of the future reinforcements, thus leading to the best scheduling. We put Q, a matrix that contains the coefficients corresponding to the probability of choosing a particular action depending on the current state. Learning algorithm goes as follows:

```
Set the parameter, and environment rewards.
Initialize matrix Q (s, a, s’) to zero.
For each episode:  Select an initial state.
  Do while there is task to schedule.
    Select one among all possible dispatching rules (DR) for
  current state.
    Using this possible DR, consider going to the next state.
    Get maximum Q (s, a, s’) value for the next state based on
  all possible actions.
    Compute: Q (s, a, s’) = Q(s, a)+ Max [Q(s’, all actions a)]
    R(s,a)= Max [Q(s’, all actions a)]
  Set the next state as the current state.
End Do. End For.
```

Simulation results of the proposed approach are described in the next section.

Table 2 Product's classes distribution

Class	1	2	3	4	5	6	7	8	9	10
Products amount	11	9	5	9	8	11	6	9	14	18

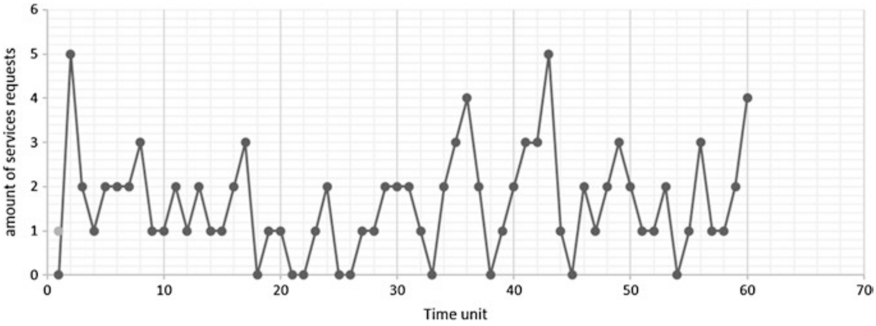

Fig. 3 Discrete time requests

4 Experimentation and Simulation

4.1 Simulation Tool and Experimental Data

For the implementation, a multi-agent system (MAS) was chosen. Being positioned on a solution based on IP, the proposed model was simulated using Eclipse environment: a Java tool compatible with JADE, the platform for the MAS architecture.

Concerning the product class, products are randomly generated with 10 classes. This diversity of classes will affect the global complexity of the problem. Table 2 shows the distribution of those classes. Figure 3 represents requests arrival in time.

4.2 Results and Discussion

The *makespan* target is important when there are a finite number of jobs. It is denoted *C*max and is defined as the time when the last job leaves the manufacturing system: *C*max = max *(C*1 … *Cn).*

The experimentation study asked services from IPs to SPs over 1,666 min. We studied the overall execution time of tasks. Shortest Job First (SJF) produced 598 makespan while FIFO (First in, First Out) over 1,629. The target criteria is a complex target function than does not depend exclusively on the overall time performance.

Our emerging decisional process provides a best solution each time by selecting the best performance indicator. Figure 4 represents a comparative result of

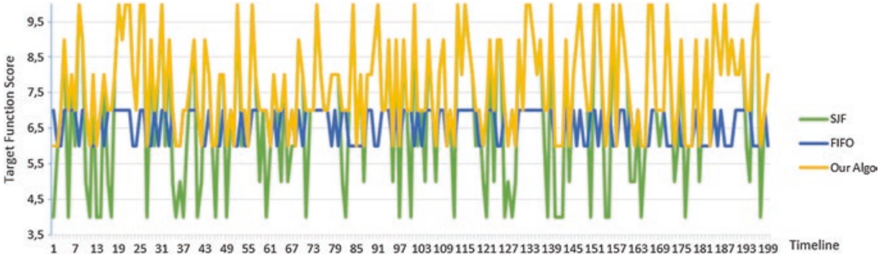

Fig. 4 Evaluation of target function's maximization scores

the performance score and illustrates the superiority of our algorithm in term of target function satisfaction. For example, at time 13 FIFO produced a score of 8 while SJF produced only a score of 3. So, our algorithm will automatically take the most efficient dispatching rule and produce a score of 8 by selecting, then using FIFO.

5 Conclusion

In this paper, our main target was to provide a proof of concept for the applicability of learning intelligent/active product in a flexible manufacturing system. Thus, we applied our model of IP to a generic manufacturing system. We presented an intelligent/active product driven model with a Q-learning capability.

We presented a literature review of relevant studies in intelligent/active product in manufacturing systems, and defined our theoretical framework. For decision-making processes an example was provided by DR selection (FIFO, SJF). Afterwards, we explained the application, discussed the results and analysed the performance of the approach.

A contextualization method is proposed to improve the decision making of the product for scheduling task. In deploying a multi-agent simulation platform, we used a Markov decisional process. Our system provides the best solution each time by selecting the best performance indicator.

Learning intelligent products in manufacturing systems provide good opportunities for the future. The active product coupled with RL method offers new chances to increase the product's performance in term of flexibility and reactivity. For future works, we attempt to explore other learning algorithms, such as TD-Learning. Another perspective is to promote contextualization to ensure a best perception of the dynamic environment. Then, an enhanced formulation of the problems encountered by active product will lead to increasing reactivity and efficiency of the decisional proficiency.

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Fuzzy Decision-Making Method for Product Holons Encountered Emergency Breakdown in Product-Driven System: An Industrial Case

Ming Li, Hind Bril El Haouzi, André Thomas and Arnould Guidat

Abstract In this paper a fuzzy decision-making method is proposed to make local decisions in case of breakdown occurring in a context of product-driven systems. To cope with breakdown uncertainty, three parameters, α, β and γ are created to evaluate the impact of it. Further, a fuzzy rule based on a membership function is designed to switch between centralized and distributed decisions concerning the re-arranging of the remaining parts. Simulation results show that appropriate decisions could be made by the proposed fuzzy decision-making method with certain suitable parameters. This method was applied on an existing industrial case; it can be easily extended to make decision for breakdown events in other contexts.

Keywords Fuzzy decision-making method · Product-driven system · Breakdown · Holonic manufacturing systems

1 Introduction

To cope with the increasing global market competition, various intelligent approaches have been suggested to improve flexibility, reconfiguration and scalability of manufacturing systems. Among them, product driven systems (PDS) based on intelligent products change the vision from passive to active products [9]. Especially, PDS significantly improve visibility, robustness and adaptation of local

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M. Li
Southwest Forestry University, Kunming, China

M. Li · H.B. El Haouzi (✉) · A. Thomas · A. Guidat
Research Centre for Automatic Control (CRAN), CNRS (UMR 7029), Nancy University,
ENSTIB, 27 Rue Philippe Seguin, 88000 Epinal, France
e-mail: hind.el-haouzi@univ-lorraine.fr

A. Thomas
e-mail: andre.thomas@univ-lorraine.fr

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decisions on the shop-floors thanks to Auto-ID technologies. The concept of PDS was firstly proposed by McFarlane in 2003 [6]; after that, it brought the attention of several research teams. Among the recent works, Herrera proposed a generic framework for PDS [5]. This proposition is an extension of their previous studies. Here, we mainly focus on how the active product can make proper local decisions in case of unforeseen events as breakdowns occurring on the shop-floor.

PDS concept sets that the product could be active and/or could take decisions. That leads to two main ways for decision making system structures: hierarchical and/or heterarchical structures. In hierarchical structure, each level is in charge to plan or schedule the production plans and to report the implementation results to the higher level. This centralized decisions structure is usually qualified to lead to poor agility and robustness. Conversely in PDS, each active product has high ability to make local decision through cooperation and interaction with other active products in heterarchical structures. Facing with unforeseen events occurring on the shop floor, the active products try to solve the problems through cooperation with other products. However, if the products are not able to solve the problem by any autonomic approaches, they will ask to switch in a centralized situation. Obviously, switching in centralized situation would lead to cost and time increases.

In the PDS, the active product can obtain the accurate breakdown starting time thanks to communication with other active products, but the ending time is not precisely known. In addition and resulting from the scheduling process, each product belongs to one lot. For this reason, when a breakdown occurs on a work centre transforming a product, this product has to decide what to do concerning itself and the other remaining products belonging to its lot. Consequently and due to the breakdown duration uncertainty, it is difficult for active products to make, as quickly as possible, proper decisions by traditional approaches. As far as we know, few researchers have tackled this problem. That is why we propose in this paper a fuzzy decision-making method to address the breakdown duration uncertainty and the way to re-schedule the remaining parts to manufacture.

In the next section, a brief overview of PDS is done. Section 3 describes an industrial PDS case which is used as research subject. A fuzzy decision-making method useful to cope with the emergency of breakdown is introduced in detail in Sect. 4. In the last section, simulation is used to analyse and compare the effectiveness of the proposed fuzzy decision-making method.

2 A Brief Review of PDS

Historically, ‘centralized’ approaches have been implemented thanks to MRP2 and ERP systems, with tools and methods mainly based on operational research concerning production activity control. In centralized approaches, decisions are hierarchically broadcasted from the higher decisional levels down to the operational units. These approaches are mainly used to provide long term optimization of production planning given a relatively stable industrial context. Facing the eighties' market challenges, various decision-making strategies have emerged. To improve reactivity and flexibility of manufacturing systems, several distributed approaches such as anthropocentric and visual management methods are proposed and used in practice. Unfortunately, these ways can only control inputs and outputs from "black boxes" and highlight the need for more and more real-time closed-loop information systems. In the 90's, manufacturing systems have changed from the traditional mass production to mass customization to cope with the increasing global market competition. High competition between enterprises and market volatility led enterprises to be more agile. In order to improve the agility of systems, various intelligent manufacturing systems (IMS) with heterarchical structures were proposed in the past two decades. The common denominator for all these systems is to bring intelligence and autonomy as near as possible to (or even in) the physical system. Among them, holonic manufacturing system [16] and agent-based manufacturing system [13] are the most attractive ones and became the typical tools to establish other intelligent systems. Borangiu proposed an implementation framework for holonic manufacturing control system for agile job shop with networked intelligent robots [1]. And then, Borangiu suggested a solution for changes occurring in resource status and production orders by global product scheduling at aggregate batch horizon [2]. Some modified architectures of holonic manufacturing systems were suggested to solve industrial cases [3, 15]. A software platform was built for holonic manufacturing systems by agent technology [3]. An agent-based control system was suggested to solve industrial cases by using RFID technology in real-time programmable logic controller based manufacturing systems [17].

Most recently, as a novel IMS, product driven systems based on intelligent products attract more researches' attention. The main difference between PDS and other IMSs is that a product can be an active actor throughout its lifecycle thanks to Auto-ID technologies. The notion of product intelligence was introduced in 2002 when several authors presented an alternate vision for the way in which supply chains might work [6, 18]. Further, various intelligent products have been used in manufacturing systems to improve flexibility and robustness [7, 8, 12, 14]. Especially, Thomas and his research team in CRAN have been paying their attention on PDS and made many achievements. Pannequin et al. [10] defined a benchmarking protocol and proposed a component-based generic architecture to support a benchmarking protocol for PDS. With simulation, they found that PDS can perform as good as traditional centralized control, and that its robustness depends mainly of the local decision-making processes. Further, Pannequin and Thomas [11] proposed a product driven system architecture based on a particular interpretation of the concept of stigmergy, where cooperation between production actors is achieved thanks to attributes attached to products. El Haouzi et al. [4] proposed a methodological approach to design a PDS and validate its feasibility and efficiency using a real industrial case. The approach is based on the six sigma method and discrete event simulation. Herrera et al. [5] proposed a generic PDS framework for dealing with production planning and control. The framework is based on viable system model (VSM), which allows modelling and considering autonomy, self-organization and adaptability for the systems.

3 Problem Description

As an extended study, the case used in this paper has the same model and parameters as in Pannequin et al. [10] and Pannequin and Thomas [11]. The case concerns a production cell of an automotive-industry subcontractor. For simplicity, we don't present the case in detail but the detailed statement of the case can be found in Pannequin's papers published in 2009 and 2012 [10, 11]. The production process is divided into two stages. The first line (called SF) manufactures semi-finished products, which are further assembled on three independent assembly lines (called FA, FB and FC). The production module includes four lines and an inventory of semi-finished products. Here, four finished products have been launched in 18 lots and the semi-finished products are handled in SF. In the further step, the lots are scheduled on the three assembly lines thanks to a centralized optimization approaches (in this paper, each *item* represents a specific product and will be divided into a series of sub-groups by certain optimization approaches and each sub-group is called *lot)*. Because the main aim of this paper is to discuss the decision mechanism useful to tackle the problem of an unforeseen breakdown, the detailed scheduling process of production in each line will be ignored and the Gantt chart of the predictive schedule is only shown in Fig. 1. The lots concerning the same items are presented with the same colour in the Gantt chart. Note that because the colour of the lots is randomly created by the computer, each figure may have different colours for the same item, but this phenomenon doesn't affect the description of the production plans.

As previously described in hierarchical systems, it is common that each level generates production schedules which will be disaggregated to the next level. In addition, if an emergency occurs in the heterarchical structure, each active product can make certain local decisions by cooperation and interaction with other

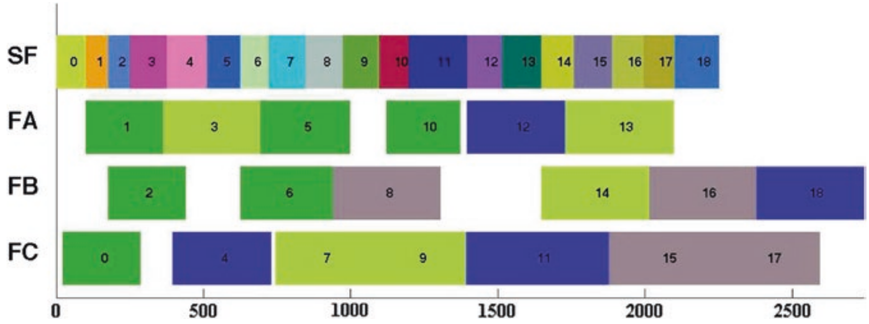

Fig. 1 Gantt chart of production plans in all lines

products. According to the interpretation provided by Pannequin and Thomas, a product-driven system is usually composed by two structures simultaneously: hierarchical and heterarchical, and then, each product is an active product and has autonomic decision ability but can also ask the hierarchical part of the system to help it to find a re-scheduling solution. Moreover, as stated before, each active product belongs to a lot according to optimization objectives. Consequently, when a product encounters an emergency, it must make a certain decision for itself and all the following products belonging to the same lot. In our case, each product has two choices to deal with the sudden breakdown: switching in a centralized situation and asking the higher level for rescheduling the plan, or making a local decision by certain automatic approaches (distributed situation). It is obvious that the former choice is the most slowly and costly way.

It is also admitted here that the active product can obtain the precise breakdown starting time but must estimate the predicted breakdown ending time through interacting with active resources. According to the uncertainty of ending time, it is difficult to determine exactly how many products need to be dealt with. On the other hand, according to the dynamic characteristics of the system, each active product continuously has to perceive the manufacturing environment and make autonomic decisions. For these reasons we suggest that only the remaining parts of the lot which encounters the breakdown needs to be dealt with. Moreover, it is the first product of this lot which has to determine to keep staying in distributed situation or not, to solve the problem.

4 Fuzzy Decision-Making Method

As mentioned before, to cope with a breakdown, the product firstly needs to determine whether to switch in centralized situation or not. It is noteworthy that it is easy to make such a decision according to the quantity of lots concerned by the breakdown if we know the accurate breakdown starting and ending times. However and as previously stated, if the starting time can be obtained precisely, the ending time is usually inaccurate in practice. As a result, the decision should be built with a predicted breakdown ending time. Although there are several research issues about product driven systems, as far as we know no research provided any decision approach with respect to breakdown events in detail. In fact, there are many factors influencing the decision process, among them and for a reactive manufacturing system, the time to decide what to do to face the unforeseen event is very important: the decision must be determined as quickly as possible. With consideration of uncertainty and rapidity, a parameter is created to evaluate the breakdown duration criticality as follows.

$$\alpha = \frac{L}{RC_T} \tag{1}$$

where L represents the duration of the breakdown, which is a predicted value provided by the resource concerned with the breakdown. RC_T represents the remaining capacity of all remaining work centres of the product routing. The remaining capacity is the sum of all idle times existing into the predictive product schedule, and the remaining capacity must be calculated according to the forecasted breakdown ending time.

Obviously, when the value of parameter α is less than one, it implies that the system has enough time to solve the situation, so a deterministic decision should be implemented to stay in current distributed situation and then deal with the emergency through certain automatic approaches. On the contrary, we can't assert that there is no enough time to cope with the breakdown when the value is more than one. For example, when the value of L is slightly larger than RC_T, a decision of switching in centralized situation could be implemented. However, if the breakdown is finished before the forecasted ending time, it is possible to deduce a value for α less than one. It means that an extra cost and time should be paid for an inappropriate decision. For this reason, it is rather risky to directly determine if we have to switch in centralized situation or not according to the value of parameter α. Using a fuzzy logic, a membership function with respect of α is generated to provide the basis for decision as follows.

$$mf(\alpha) = \begin{cases} 0 & \alpha < 1 \\ \frac{\alpha-1}{t-1} & 1 \leq \alpha < t \\ 1 & \alpha \geq t \end{cases} \tag{2}$$

where t is an available parameter decided by the user. Through changing the value of t, different function values can be obtained for the same variable α in the interval $(1,t)$.

Then, the decision will be made under the following rule based on the function values: *if the function value mf(*α*) is more than* p_α*, then switch in centralized situation, otherwise, stay in current distributed situation.*

Here, p_α is a value of the threshold determined at interval (0,1) to cope with the uncertainty of the breakdown event. For the same values α and t, larger value of p_α means the centralized situation may be selected with smaller probability and vice versa. Combining with parameter t, it is easy to change the switching threshold between two situations. For example, if p_α and t are set to 0.3 and 2 respectively, when the value of α is 1.5, the decision of switching in centralized situation will be implemented according to the function value (0.5) computed if the above formula is more than p_α (0.3).

However, when the value of t increases to 3, a contrary decision will be adopted according to the fact that the new function value (0.25) is less than p_α (0.3). It is obvious that when the value of α is more than one, the decision of switching in centralized situation will be adopted with lower probability, while the value p_α or t increase.

Once the active product has decided to stay in current distributed situation, it has two ways to deal with the breakdown. The first one is to keep waiting until the breakdown is eliminated, and the other way is to re-arrange the remaining products of the lot by certain autonomic approaches. For simplicity, the former decision is denoted as DC_1 and the latter is denoted as DC_2. Obviously, DC_1 is the simplest method to deal with the breakdown.

Without changing the production order, the remaining lots will be suggested to have the same delay, which is equal to the breakdown length. Due to the fact that the due date remains the same, such decision will not affect the scheduled production plan. Contrarily, DC_2 usually needs to change the scheduled plan by interacting among the active products to cope with the breakdown. As stated before, according to the uncertainty and dynamic characteristics and among the remaining scheduled lots, only the first lot needs to be dealt with. Note that one basic premise of waiting decision is that there is enough idle time (slack) to absorb the breakdown. The other key factor is the quantity of remaining parts of the first lot. In order to evaluate these two factors, two parameters are defined as follows.

$$\beta = \frac{L}{RC_B} \quad \text{and} \quad \gamma = \frac{RL_B}{RC_B} \tag{3}$$

where the variable RC_B represents the remaining capacity of the line taking into account of the breakdown, the value of RC_B is equal to the total idle time remaining after the predicted ending time taking into account of the breakdown (slack time). RL_B represents the production time of the remaining parts of the first lot that needs to be dealt with. Note that RL_B can be also used to evaluate the quantity when it is divided by the unit production time. With consideration of breakdown uncertainty, the values of β and γ are divided into two classes, *small* and *larger*, and then two membership functions are created for each parameter as follows. It implies that β can be regarded as a *small* with the probability of $\mu_{S\beta}(\beta)$ and a *larger* with the probability of $\mu_{L\beta}(\beta)$. It is the same case for γ.

$$\mu_{S\beta}(\beta) = \begin{cases} 1-\beta & 0 \le \beta < 1 \\ 0 & otherwise \end{cases} \quad \text{and} \quad \mu_{L\beta}(\beta) = \begin{cases} \beta & 0 \le \beta < 1 \\ 1 & \beta \ge 1 \\ 0 & otherwise \end{cases} \tag{4}$$

$$\mu_{S\gamma}(\gamma) = \begin{cases} 1-\gamma & 0 \le \gamma < 1 \\ 0 & otherwise \end{cases} \quad \text{and} \quad \mu_{L\gamma}(\gamma) = \begin{cases} \gamma & 0 \le \gamma \le 1 \\ 0 & otherwise \end{cases} \tag{5}$$

Then, two rules are *generated* to make decision between DC_1 and DC_2 for each parameter. Traditional fuzzy techniques induce discrete outputs, so there are no fuzzy classification and defuzzification steps for the outputs here. For this reason, the rules are described as follows:

- if β is small, then DC_1 is selected with the probability $\mu_{S\beta}(\beta)$
- if β is large, then DC_2 is selected with the probability $\mu_{L\beta}(\beta)$
- if γ is small, then DC_1 is selected with the probability $\mu_{S\gamma}(\gamma)$
- if γ is large, then DC_2 is selected with the probability $\mu_{L\gamma}(\gamma)$

Without any defuzzification process, selection between two decisions can be simply implemented by comparing the probability values obtained. At first, min or max operator is used to evaluate the final selection probability of each decision. For example, to a deterministic β and γ, two selection probabilities of DC_1, $\mu_{S\beta}(\beta)$ and $\mu_{S\gamma}(\gamma)$ are obtained by the first and third rule, and we assume that $\mu_{S\beta}(\beta)$ is greater than $\mu_{S\gamma}(\gamma)$. If a min operator is adopted, the final selection probability of DC_1 is $\mu_{S\gamma}(\gamma)$. Conversely, DC_1 has a final selection probability of $\mu_{S\beta}(\beta)$.

Then, the decision with higher selection probability is finally adopted to deal with the breakdown. For example, if β and γ are 0.2 and 0.7 respectively, then we can get the values of probabilities: $\mu_{S\beta}(\beta) = 0.8$, $\mu_{L\beta}(\beta) = 0.2$, $\mu_{S\gamma}(\gamma) = 0.3$ and $\mu_{L\gamma}(\gamma) = 0.7$. With min operator for DC_1 and max operator for DC_2, we can conclude that the final selection probabilities of DC_1 and DC_2 are 0.3 and 0.7 respectively. Consequently, the final decision is DC_2 for its higher selection probability.

According to the above analysis, three decisions could be selected to deal with the breakdown: switching in centralized situation (denoted as DC_3 for convenience), waiting for repairing (DC_1) and make local decisions to arrange the remaining parts of the first lot (DC_2). A fuzzy decision-making method based on three parameters (α, β and γ) is provided to solve this problem. As mentioned before, when DC_3 is adopted, the re-schedule decision will be done by the higher level. The solution of scheduling problems in this higher level is not the research focus in this paper, so how to deal with the breakdown in DC_3 will not be discussed in detail. In DC_1 case, the lots needn't to do anything but the new production starting time will be found according to the breakdown duration. Consequently, we focus our research on the way to solve the DC_2 case.

As stated before, only the remaining parts of the first lot need to be dealt with when DC_2 is adopted. The basic principle of solution in DC_2 is to save the setup cost and reduce its impact on other scheduled lots. The concerned active product firstly looks for the longest idle time in the schedules of all lines. If the idle time is long enough to arrange all the remaining parts of the first lot, obviously an acceptable solution is to manufacture this remaining parts during this idle time; otherwise, enlarge the longest idle time through advancing or delaying the production of relative lots would be another way. And then, the remaining products ought to be put together with the lots of similar products as much as possible. Without enough idle time, the remaining products should be divided into sub-lots and distributed in several idle intervals. The flow graph of the fuzzy decision-making process and the decision procedure of DC_2 are shown in Figs. 2 and 3.

Notations in the figures are listed as follows.

RC_T	total remaining capacity of all lines
RC_B	remaining capacity of the line with breakdown
RL_B	quantity of the first lot after the predicted breakdown ending time
DC_1	waiting for repairing
DC_2	make local decisions to arrange the remaining parts of the first lot
DC_3	switching in centralized situation
RL	the first lot after the starting time of the breakdown
C_1	there are lots belonged to the same item of RL among all the remaining lots
C_2	there is an enough idle interval more than the production time of RL
D&D	divide and distribute RL according to the length of idle intervals
Max(x)	maximize the idle time of x through advancing or retarding the lots

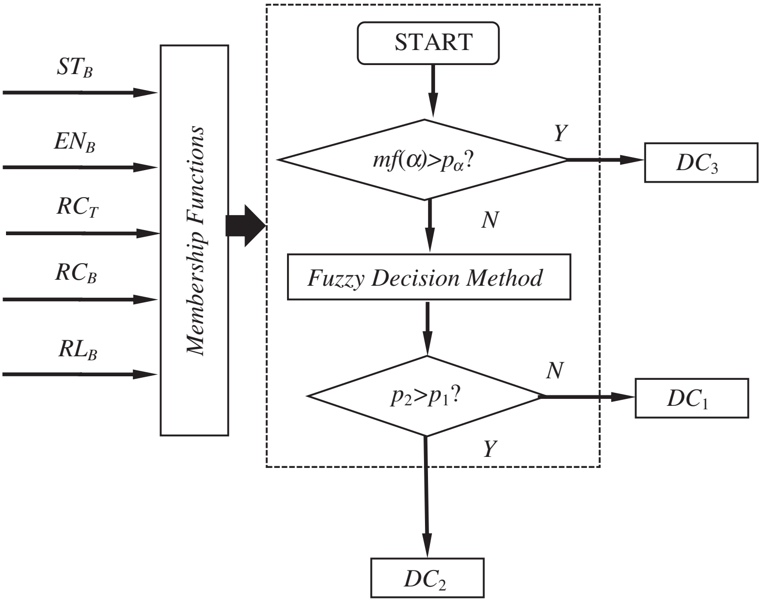

Fig. 2 The flow graph of fuzzy decision-making process

5 Simulation

In order to verify the effectiveness of the proposed fuzzy decision-making method, 8 typical breakdowns are generated in different lines and the final decisions are made with four combinations of min and max operators. The production limitation of all three lines is set to 2,800. The final decisions of each case are summarized in the following Table 1. Case 4–6 are used to analyse the influence of parameters p_α and t, the values of (p_α, t) are (0.2, 1.5), (0.3, 1.5) and (0.2, 2.0) for case 4–6, respectively.

In other cases, the values of p_α and t are not considered because the value of α is always less than one. If the decision of DC_3 is abandoned, four different combinations of two operators are used to take the final decision: (min(DC_1), max(DC_2)), (max(DC_1), min(DC_2)), (max(DC_1), max(DC_2)) and (min(DC_1), min(DC_2)), and the results are successively recorded in the last column of Table 1. Following we use the case 1 to explain the decision process.

In case 1, the breakdown occurs in assembly line FB with the starting time of 1,400 and the predicted ending time of 1,550. Because the function value of $mf(\alpha)$ is less than one, DC_3 is firstly abandoned. According to the membership functions and decision rules of parameters β and γ, for parameter β DC_1 is selected with the probability of 0.037 and DC_2 with the probability of 0.963. Similarly, the two probabilities are 1 and 0 respectively for parameter γ. Then, four different methods are used to make the final decision. Firstly, (min(DC_1), max(DC_2)) is used

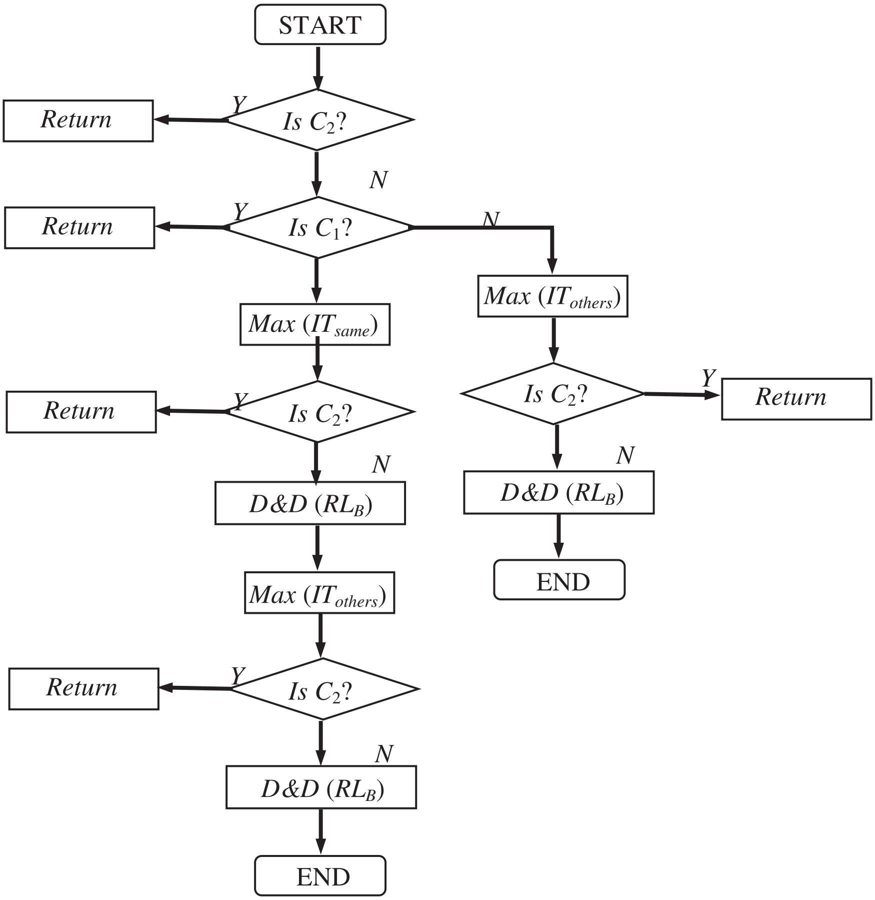

Fig. 3 The flow graph of decision procedure in DC_2

to evaluate the selection probability of DC_1 and DC_2. As the result, the selection probability of DC_1 is 0.037 for min operator and that of DC_2 is 0.963 for max operator. Because DC_2 has higher selection probability, the final decision is DC_2. Similarly, (max(DC_1), min(DC_2)) operators can obtain the selection probability of 1 and 0 for DC_1 and DC_2, which leads to the final decision of DC_1. The results of two selection probabilities in (max(DC_1), max(DC_2)) and (min(DC_1), min(DC_2)) are (1, 0.963) and (0.037, 0), respectively. Consequently, the final decision is DC_1 in these two methods. The Gantt charts of solution are drawn in the figures included in Appendix when DC_2 is implemented.

In case 1, although there is no lot during the breakdown interval, the first lot (lot 14) after the breakdown starting time is still re-arranged behind the lot 13 when (min(DC_1), max(DC_2)) is implemented (see Fig. 4).

Obviously, if the breakdown finishes at predicted ending time, it is not a proper strategy to select DC_2 for an extra change cost. However, when the length of the

Table 1 Final decision with different combination of operators

Case	Breakdown	$mf(\alpha)$	Decision (β)	Decision (γ)	Final decision
1	1,400 ~ 1,550 (FB)	0	$0.963/DC_2$	$0/DC_2$	DC_2
					DC_1
			$0.037/DC_1$	$1/DC_1$	DC_1
					DC_1
2	450 ~ 600 (FB)	0	$0.350/DC_2$	$0/DC_2$	DC_1
					DC_1
			$0.650/DC_1$	$1/DC_1$	DC_1
					DC_1
3	200 ~ 2,200 (FC)	0.266	–	–	DC_3
4	200 ~ 2,200 (FC)	0.266	$1/DC_2$	$0.042/DC_2$	DC_2
					DC_1
			$0/DC_1$	$0.957/DC_1$	DC_2
					DC_2
5	200 ~ 2,200 (FC)	0.133	$1/DC_2$	$0.042/DC_2$	DC_2
					DC_1
			$0/DC_1$	$0.957/DC_1$	DC_2
					DC_2
6	950 ~ 1,100 (FA)	0	$0.199/DC_2$	$0.312/DC_2$	DC_1
					DC_1
			$0.801/DC_1$	$0.688/DC_1$	DC_1
					DC_1
7	0 ~ 100 (FB)	0	$0.15/DC_2$	$0/DC_2$	DC_1
					DC_1
			$0.85/DC_1$	$1/DC_1$	DC_1
					DC_1
8	1,850 ~ 2,700 (FA)	0	$1/DC_2$	$0.288/DC_2$	DC_2
					DC_1
			$0/DC_1$	$0.711/DC_1$	DC_2
					DC_2

breakdown becomes very large, it is a good way to make effective decision in advance. We can conclude that (min(DC_1), max(DC_2)) is the most positive strategy. In all cases, (max(DC_1), min(DC_2)) is the most conservative strategy because it always trends to make decision only between DC_1 and DC_3, waiting or switching in centralized situation. Except in case 1, the other two strategies have the same decisions as which with (min(DC_1), max(DC_2)). Comparing case 3, 4 and 5, facing to the same breakdown, different decisions of switching between centralized and distributed situations are determined through changing the parameters of membership function of α (see Figs. 5 and 6). Such comparison illustrates that the selection probability of DC_3 can flexibly controlled by the parameters p_α and t. The remaining part of the first lot is divided into two parts (see Fig. 7) and arranged in two idle intervals in the last case because there is no enough idle time to arrange the whole remaining part.

6 Conclusion

Using an industrial case, a fuzzy decision-making method is proposed to deal with unforeseen breakdowns. At first, to cope with breakdown uncertainty, a parameter α and its membership function are used to decide to switch in centralized situation or not. Especially, the selection probability of two different situations can be adjusted easily by resetting the parameters p_α and t in membership function. This idea can increase flexibility and adaptability of local autonomic decision-making process. Once the decision is to stay in current distributed situation, two parameters β and γ are used to evaluate the impact of the breakdown. And then, four membership functions, four fuzzy rules and two operators are designed to choose between two decisions, waiting for repairing and re-arranging the remaining parts. Lastly, a local re-arranging approach of the remaining parts is proposed and described in detail. Simulation results show that proper decisions could be obtained using the proposed fuzzy decision-making method with correct selection of operators. Although the fuzzy decision-making method is proposed for a specified case, it can be easily extended to deal with breakdown events in other manufacturing systems. In our future work, we will consider some other factors such as due date and changing cost in the fuzzy decision-making method.

Appendix

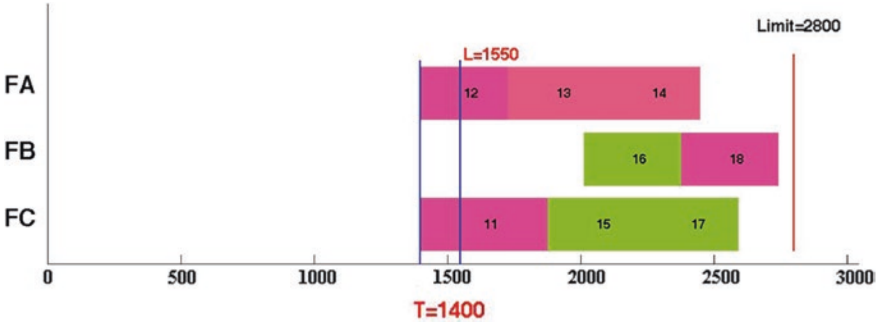

Fig. 4 Re-scheduled plan of remaining lots in case 1

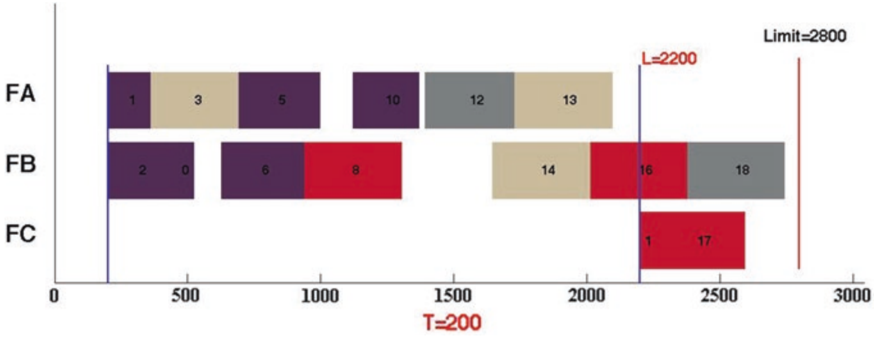

Fig. 5 Re-scheduled plan of remaining lots in case 4

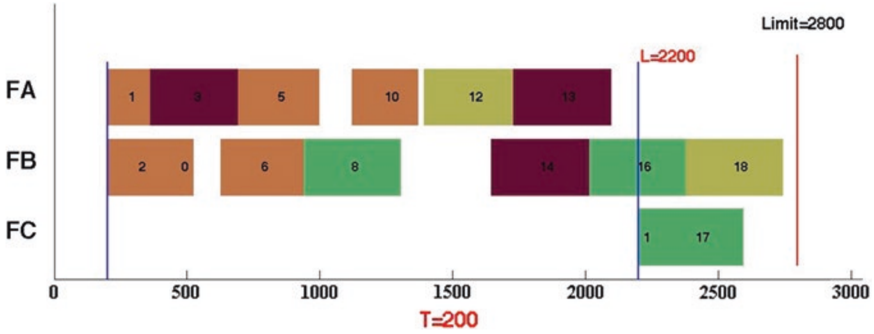

Fig. 6 Re-scheduled plan of remaining lots in case 5

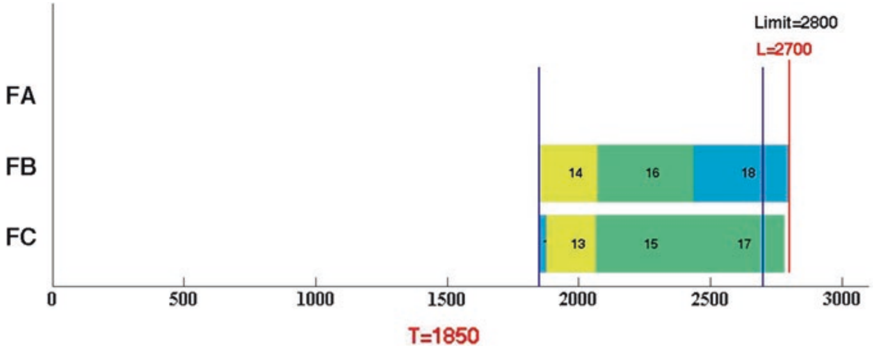

Fig. 7 Re-scheduled plan of remaining lots in case 8

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Part VI

Physical Internet Simulation, Modelling and Control

On the Activeness of Physical Internet Containers

Yves Sallez, Benoit Montreuil and Eric Ballot

Abstract The aim of the innovative Physical Internet (PI) concept is to reverse the unsustainability situation existing in current logistic systems. In the PI approach, the goods are encapsulated in modularly dimensioned, reusable or recyclable and smart containers, called PI-containers. This paper focuses on the design of such containers and more particularly on their associated activeness. This capability allows the PI-container to have an active role for its mission and in the PI management and operation. After a presentation of the physical and informational requirements associated to PI-containers, the notion of activeness is detailed and the main research issues are presented.

Keywords Physical internet · Smart container · Activeness · Intelligent product

1 Introduction

According to [1, 2] the current logistic systems are known to be unsustainable economically, socially and environmentally. To concurrently reverse this situation on the three points of view, the authors introduce the innovative Physical Internet

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Y. Sallez (✉)
University of Lille Nord de France, 59000 Lille, France
e-mail: yves.sallez@univ-valenciennes.fr

Y. Sallez
TEMPO Lab, Production, Services, Information (PSI) Team, UVHC, 59313 Valenciennes, France

B. Montreuil
Canada Research Chair in Business Engineering, CIRRELT, Université Laval, Québec, Canada

E. Ballot
CGS, Mines ParisTech, Paris, France

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(PI) concept. This interconnected logistics system is based on a metaphor of the Digital Internet. By analogy with data packets, the goods are encapsulated in modularly dimensioned, reusable and smart containers, called PI-containers. The ubiquitous usage of PI-containers is to make it possible for any Logistics Service Provider to handle and store any company's products because it will not be handling and storing products per se. In that context, the design of efficient and adequate PI-containers is a main issue. Both physical and informational aspects must be considered in this design. Indeed a PI-container must not be considered as only a "standardized" container with a cargo. As outlined in [2], PI is to exploit as best as possible the capabilities of smart PI-containers connected to the Internet of Things, and of their embedded smart objects, for improving the performance perceived by the clients and the overall performance of logistics systems and of the Physical Internet. Through the increasing of its communicational and decisional capabilities, the PI-container can play an "active" role by itself in the PI management. This paper introduces the notion of PI-container activeness and highlights the main research issues in this field.

Nowadays logistics deals only with passive (bar coded or passive RFID) objects. This situation limits the available information both in frequency and accuracy. For instance, in many supply chains the actual lead-time at the pallet or card box levels is not known. Usually, retailers do not even know the exact shipping location of inbound goods (often different from the manufacturing place). Despite the anticipated benefits, the cost of reading the high flow of data required to reach accurate and real-time information is still too high for widespread adoption.

The reliance on active objects is a way to overcome this problem by autonomous communication not only to gather information but also to enable decision-making processes that will open new savings opportunities such as real-time routing to the market and accurate withdrawal.

The paper is organized as follows. The physical and informational requirements for the design of PI-containers are introduced in Sect. 2. Section 3 describes the notion of activeness, in general and in the context of PI-containers, and then introduces different classes of activeness. Section 4 proposes different research issues in the field of PI-container activeness. Finally conclusive remarks are offered in the last section.

2 Requirements for the Design of PI-Containers

The fundamental PI concept relies on the use of standardized containers that are the fundamental unit loads. Physical goods are not directly manipulated by the PI but are encapsulated in standardized containers. These containers are moved, handled and stored in the PI network. The physical and informational requirements are respectively presented in the two following sections.

2.1 Physical Requirements

As exposed in [1, 2], the key functional specifications of PI-containers are:

- Coming in various modular sizes, from the cargo container sizes down to tiny sizes;
- Easy to handle, store, transport, seal, clench, interlock, load, unload, construct, dismantle, panel, compose and decompose;
- Made of environment friendly materials, with minimal off-service footprint;
- Minimizing packaging materials requirements through the enabling of fixture-based protection and stabilization of their embedded products;
- Coming in various usage-adapted structural grades;
- Having conditioning capabilities (e.g. temperature) as necessary;
- Sealable for security purposes.

As introduced in [3], three PI-containers categories can be distinguished: transport, handling and packaging containers. The relationships between the different categories of PI-containers and the physical goods they are to encapsulate are summarized in Fig. 1.

- The **transport containers**, or T-containers, are the large entities transported by the different types of vehicles (trucks, trains, ships…) on the PI networks. They are designed to be easily carried, to endure harsh external conditions and to be stackable as usual maritime shipping containers. They can contain physical

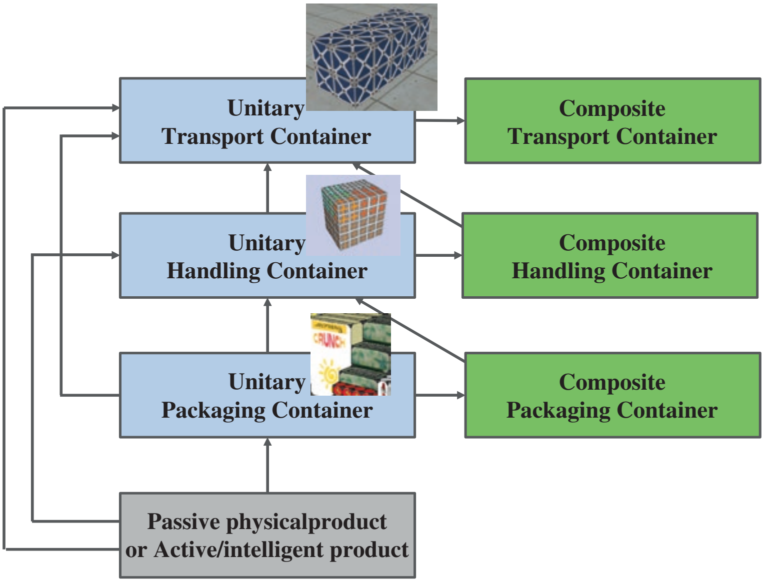

Fig. 1 Illustrating the relationships between the three categories of PI-containers

goods directly and/or PI-containers of smaller size. They have modular external dimensions on the order of 1.2, 2.4, 3.6, 4.8, 6 or 12 m. Sections with width and height both being either 1.2 and 2.4 m allow the T-containers to fit in current carriers.

- The **handling containers**, or H-containers, contain physical goods and/or PI-containers of smaller size. They are designed to be easily handled by PI-handlers (conveying systems, lifts…) and to resist rough handling conditions in the different nodes of the PI network. The typical maximal modular external size of an H-container allows it to fit into a T-container with external sides of 1.2 m. Available smaller external modular dimensions along the X, Y and Z axes are on the order of 50, 40, 30, 20 down to 10 % of this maximum size. H-containers are stackable at least 2.4 m high to fit in T-containers and PI-carriers (e.g. dry-bed trailers adapted to PI specifications).
- The **packaging containers**, or P-containers, are used to contain directly the physical goods. They are dimensioned to modularly fit in H-containers. As thin and light a possible, they are designed to be easy to insert and extract, to be able of protecting the product and to be stackable as necessary. They basically replace the typical custom packaging, for example designed to market goods. They offer easy customized panelling for marketing and informational purposes. They can be used to present the products in stores and to store the products at usage locations such as homes.

As depicted in Fig. 2, in a same category, the PI-containers can be composed and interlocked to build "composite" PI-containers and allow easier handling or transport, sharing the same standard type of interfacing devices.

The design of PI-containers is under study in two complementary interconnected fast-moving consumer goods (FMCG) logistics research projects. The European MODULUSHCA project focuses on the design of H-containers (termed

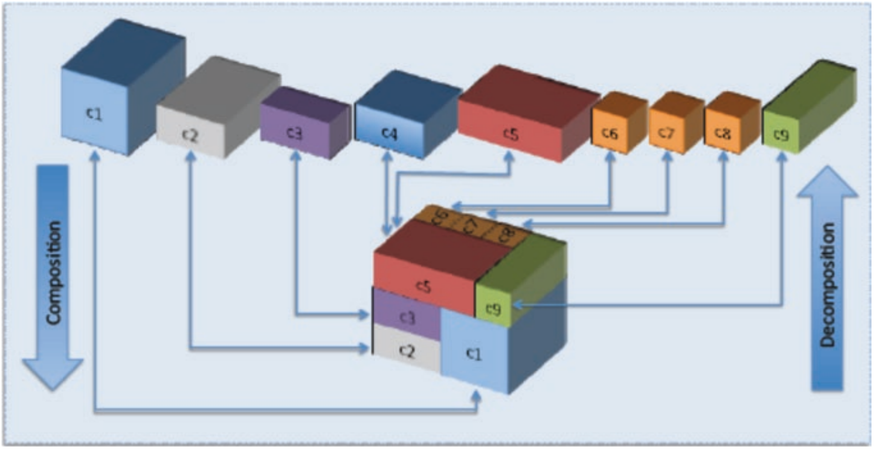

Fig. 2 Example of composition/decomposition of PI-containers

M-boxes in the context of that project), with the aim of building and testing physical prototypes of such H-containers [4]. The North American LIBCHIP project extends the design effort to encompass the three categories of PI-containers, up to the level of virtual prototypes [3]. In collaboration with these projects, the research exposed in this paper focalizes on the informational design of PI-containers, and more precisely on their intelligence design.

2.2 Informational Requirements

From an informational point of view, some requirements must be fulfilled:

- *Identification*: Each PI-container must have a unique worldwide identifier similar to the MAC access in the Digital Internet. This number is already defined by EPCglocal standard with the GRAI code for Global Returnable Asset Identifier [5, 6].
- *Traceability and tracking*: The PI-management systems must be able to locate each PI-container and to provide traceability information (e.g. status, arrival and departures dates in PI facilities, environmental conditions when necessary). Here also the standard exists with the EPCglobal BizStep and Global Location Number [5, 6].
- *Integrity*: The PI-management systems are responsible of the integrity of the cargo located in the PI-containers. For example, it implies obtaining information on the respect of the cold chain for perishable goods or on the opening of containers to prevent theft.
- *Confidentiality*: The content of a handling or transport PI-container must be known only by authorized parties according to their rights. These PI-containers must remain “black boxes” for the other actors of the PI-network. This implies data encryption and enhanced access right management.

The actual developments in sensor networks, wireless technologies, GPS and the increasing research effort in Internet of Things [7], cyber physical systems and intelligent products [8] offer the tools to support these requirements. In this context, the notion of PI-container activeness is introduced in the next section.

3 Concept of PI-Container Activeness

The concept of product activeness has been introduced by [9, 10]. Via an amplification of its informational, communicational and decisional capabilities, an active product is considered as an entity capable of interacting with the different support systems (e.g. manufacturing systems, supply chains, maintenance systems) during the successive phases of its life cycle.

Applied to the PI context, some communication, memory and processing capabilities can be associated to the PI-container to make it active so as to support the previously introduced informational requirements. A PI-container is then able to play an active role in the PI management and operations, contrasting with a traditional approach in which current containers are not able to take initiatives by themselves.

3.1 Brief Description of PI-Container Activeness

As mentioned in the introduction, Internet-of-Things related devices are undergoing a fast evolution in capability and costing. Currently, there are still implementation hurdles that would prevent implementing full activeness capabilities into PI-containers. So, a phased introduction of PI-container activeness is foreseen.

Early on, minimal activeness capabilities to be implemented include scheduled reporting and event triggering. With such capabilities, the container is able to identify its state and report it, compare its state with the desired one, and send information (e.g. warnings) when certain conditions are met.

In further stages, more complex capabilities can be installed, such as defining new goals and adapting current goals, communicating with other containers, negotiating with routing agents, and learning for individual and collective experience.

According to the different categories of PI-containers presented in Sect. 2, in further stages activeness is to ever more exploit interactions of a collective set of PI-containers on several layers, as well as with the other PI means and agents.

An example of three-layer activeness is provided in Fig. 3: a P-container #p containing several passive goods is placed in a H-container #h, itself contained in a T-container #t. At each layer, a PI-container can exploit different information sources to support its activeness:

- Proprioceptive information from information sources on the PI-container itself and on its cargo:
  - Embedded static or dynamic data associated to the PI-container (e.g. ID number, references of the cargo);
  - Measurements obtained via sensors on its own physical shell and skeleton (e.g. detection of shocks or of opening tentative) or on its inside physical environment (e.g., internal temperature), identified as 1 in Fig. 3;
  - Interactions with active PI-container(s) (often of lower categories) or “active” products that are encapsulated within its cargo (2).
- Exteroceptive information obtained via interaction with:
  - Its external physical environment (e.g., temperature, hygrometry) using sensors (3);
  - Other active non-encapsulated PI-containers, mostly of the same category (4);
  - The PI Management Systems (PIMS) in the wide sense, including means and agents (5).

In Fig. 3, the interactions denoted by numbers with the symbols ’ and ” concern respectively the H-containers and the P-containers.

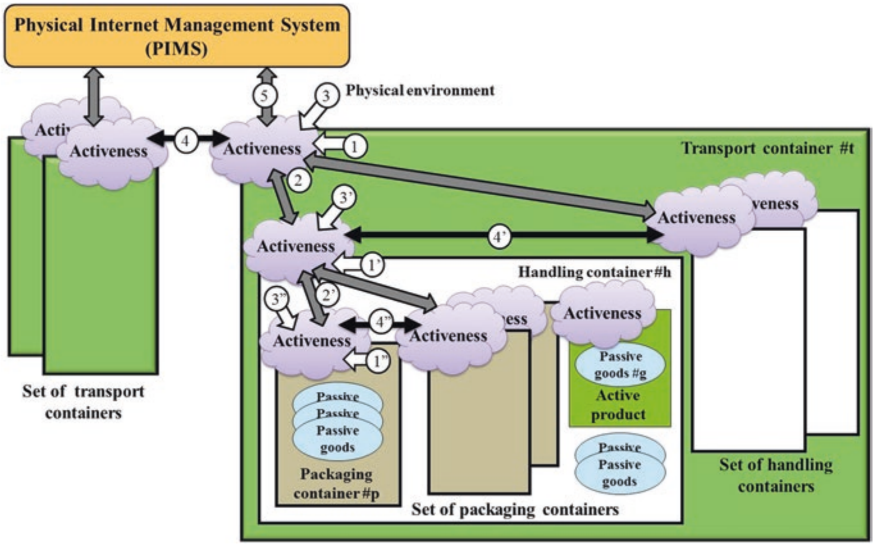

Fig. 3 Illustrating PI-container activeness

Interactions (2), (2') and (5) allow communication between the PIMS and a PI-container independently of its place in the layered hierarchy. For example, an alert generated by an encapsulated P-container #p must be transmitted to the PIMS through the two PI-containers #h and #t in which it is located.

Interactions (4), (4') and (4") between PI-containers on the same layer are mainly used to exchange information on their respective contexts and allow reduction of false alarms. For example, a PI-container can compare its measure of current external temperature to the temperatures measured by the others nearby. In case of discordance on the measurements, no temperature alarm is sent to the PIMS but a signal is rather sent to have its temperature sensor controlled. In addition, according to the level of sensors equipping the PI-containers, some redundancies can be exploited. For example, in Fig. 3, the measures (3') from sensors concerning the exterior of the handling PI-container #h (e.g. temperature) can be compared with the measures (1) concerning the interior of the transport PI-container #t when both are active, aware of each other, and communicating amongst themselves.

The activeness of products contained in the PI-containers can equally be exploited if compatible with the transmission protocols used by PI-containers and the respect of access rights.

3.2 Classes of PI-Container Activeness

As outlined in [11], activeness must not be analysed as an all-or-nothing capability. It must rather be comprehended as being actionable function by function.

Indeed a PI-container can be “passive” for a function f_i and “active” for another function f_j. According to the analysis framework proposed in [11], four classes can be distinguished according to the role taken by a collective of PI-containers in the decisional process associated to a specific function:

- *Class 1* corresponds to a group of passive containers. The PIMS (often distributed through multiple agents) takes all decisions relevant of the function. It collects itself the information relative to the PI-containers and manages the entire decision-making process of the function based on the latest known state. PI-containers are only information carriers. Basic traceability or tracking functions are representative of this class [12]. The PI-containers are equipped with RFID tags or the likes, containing static or dynamic data. Data is read or written via readers located in the infrastructure of the PI network.
- *Class 2* characterizes a group of active PI-containers playing a triggering role in the decisional process, yet letting the other steps of the decisional process to be managed by the PIMS. Monitoring functions are typical of class 2. The PI-container equipped with adequate sensors can detect a problem (e.g. abnormal high temperature), check for detection integrity with nearby PI-containers when pertinent, and send an alert message to the PIMS. The latter is then responsible to deal with this situation and to find an adequate solution.
- *Class 3* is representative of a decisional process managed entirely by a group of active PI-containers. The PIMS and the PI infrastructure are only used to provide the services necessary to realize the function. The management of incompatibility between PI-containers is an example of function of the third class. This function avoids the proximity of containers carrying cargos incompatible with each other (e.g. chemical products that can contaminate each other or cause an explosion). As an example, when a PI-container arrives in a PI-hub, it sends to the PIMS the list of elements incompatible with its cargo. (For confidentiality reasons, the detailed composition of the cargo is not sent to the PIMS). After having checked with the other PI-containers in or moving toward the PI-hub, the PIMS sends in return a list with the identifiers of the PI-containers to avoid. Using this list, the concerned PI-containers can detect any incompatibility during their routing in the PI-hub and send alert messages to the PIMS.
- *Class 4* is characteristic of a self-organized collective. The active PI-containers are self-sufficient and are able to provide services that were obtained from the PI infrastructure in the previous classes. In [13], the authors exhibit a function of collision avoidance, relevant of this class. With the capability level of this class, during a routing process in a cross docking PI-hub, transport PI-containers having to book access to conveying modules could exchange with those modules and among themselves, without decisional interaction with the PIMS.

4 Current Issues for Research Works on “Active” PI-Containers

Two groups of research issues are induced when considering activeness of PI-containers, respectively from theoretical and technological perspectives.

First, from a theoretical point of view, research works must allow to:

- Characterize and assess the main benefits of activeness from the perspective first of the localized decision points, second of the current and next phases of the total product life cycle, and third of the supply chains through the interconnected logistics networks.
- Identify precisely the different levels of activities: identification, data support, communication and alarms sending or more complex activities (negotiation, learning).
- Provide an analysis framework allowing a detailed classification of the different activities.
- Provide guidelines to choose between embedded intelligence and remote intelligence. In fact, according to the function to be supported and the desired performances, the location of the intelligence is an important point to consider. Embedded intelligence allows taking into account more precisely the local environment but needs generally more costly equipment.

Secondly, from a technological point of view, research works must deal with the following issues:

- How to adapt activeness on demand? To adapt the level of activeness according the wishes of the PI users and the cargo value, the embedded informational modules must be adaptable or exchangeable. Indeed, different technologies (RFID tag, sensors, and embedded processors) must be added and removed easily to equip adequately the PI-containers according to the intended level of activeness.
- How to realize the physical integration in the container? Linked to the previous issue, it is crucial to study the physical integration of the informational equipment in the different types of PI-containers. Notably, for the Transport PI-container, the equipment must be able to face harsh environmental and handling conditions.
- Which type of transmission should be used to support the interactions between PI-containers? The retained technology must be able to support short-range data transmission (from one to several meters) in closed and/or open environments that are in general more controlled for the packaging and handling PI-containers.
- Which type of transmission should be used to support the interactions between PI-containers and PIMS? The retained technology must be able to support long-range data transmission, up to many kilometres, for transporting PI-containers, while for the other types the need for long-range transmission depends on the fact that it is to be relayed through the technologies of the transport PI-containers and carriers encapsulating them.

5 Conclusion

In the innovative field of the Physical Internet, the design of efficient PI-containers constitutes a cornerstone. This exploratory paper started by an overview in the field of the PI-container design, with an emphasis on the requirements attached to the design of PI-containers. Then it proposed the notion of PI-container activeness. Following a brief presentation of the activeness concept in general, it has then fleshed it in the Physical Internet context, notably through a four-class characterization of activeness capabilities. Finally, several research issues in the field of active PI-containers have been proposed.

If the current European project Modulushca [4] can be considered as a first step in the design and prototyping of PI-containers, focused on the handling PI-containers, some important research efforts must be realized in the next years to build active PI-containers capable of operational autonomy and interaction in a wide range of industrial applications. Priority is expected to be first on transport and handling PI-containers, with packaging ones being tackled as cheap small enabling technologies become available. The authors' research teams are cooperating to refine the concept of PI-container activeness in a French ANR funded research project, called PI-NUTS, focused on Physical Internet cross docking hub control system.

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Adaptive Storage Location Assignment for Warehouses Using Intelligent Products

Nikolaos Tsamis, Vaggelis Giannikas, Duncan McFarlane,
Wenrong Lu and James Strachan

Abstract Due to rapidly changing customer preferences, order-picking has become a bottleneck for the efficiency of the order fulfilment process and in turn a burden to the customer satisfaction of warehouse companies. Improved storage location assignment of newly delivered products is one effective method for improving the picking performance. However, most of the available storage policies provide static solutions that do not deal with frequent changes in order demand characteristics. This study aims to identify a potential solution by developing a distributed, adaptive strategy for the storage location assignment problem and follows the product intelligence paradigm for its implementation. The efficiency of such a strategy in real industrial systems is explored via a simulation study using data from a local e-commerce fulfilment warehouse.

Keywords Adaptive storing · Warehouse management systems · Product intelligence

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N. Tsamis · V. Giannikas (✉) · D. McFarlane · W. Lu
Institute for Manufacturing, University of Cambridge, Cambridge CB3 0FS, UK
e-mail: eg366@eng.cam.ac.uk

N. Tsamis
e-mail: tsamis.nikos@gmail.com

D. McFarlane
e-mail: dcm@eng.cam.ac.uk

W. Lu
e-mail: wl296@eng.cam.ac.uk

J. Strachan
James and James Fulfilment Ltd, Sawston CB22 3TJ, UK
e-mail: js@doublejames.com

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1 Introduction

Nowadays, the rapidly changing preferences of customers result in customer orders of higher product variety, smaller order size and reliably shorter response time [1]. Such order fulfilment requirements challenge the efficiency of warehousing processes. Among the four main warehousing processes (receiving, storing, order-picking and shipping), order-picking is the most labour-intensive and costly process in warehouses with manual systems [2]. Moreover, any underperformance in order-picking can lead to unsatisfactory service and higher operational costs not only for the warehouse, but also for the whole supply chain [2]. There are many methods to improve the picking performance; one of which is by improving the storage-location assignment of the products in the warehouse in preparation for the order-picking process [3].

Currently, there are many ways that storage-location assignment can be conducted in warehouses [2, 4], however, none of those is adaptive to (increasingly frequent) changes in the customer demand. Recently, adaptive approaches which allow newly delivered products to continuously change their storage location have been introduced and studied in the literature [5]. Because of the distributed nature of such adaptive strategies, it has been proposed that the concept of product intelligence could be used as platform for their implementation in warehouse management systems [6], In this study, motivated by industrial needs of warehouse organisations as well as the opportunities provided by the intelligent product paradigm [7], we develop an adaptive storage assignment strategy aiming at improving the picking performance of a warehouse. A simulation model of a real industrial warehouse is developed and used to conduct a research experiment study and evaluate the impact of the adaptive strategy on picking performance.

2 Background

2.1 Improving the Performance of the Order-Picking Process

The most important objective of the picking process is to maximise the service level having constraints of labour, equipment and capital [8, 9]. The crucial step between order-picking and the service level is the time an order can be picked and be available to be shipped to the customer, since if an order misses its shipping due time, it will probably have to wait until the next shipping period [8]. Besides that, short order retrieval times imply high flexibility in handling late changes in orders. As a result, the picking process has the goal to minimise the order-picking time [9] which is normally considered as a waste since it costs labour hours but does not add value. In particular, the travel time to pick an order, which refers to the length of the picking tour starting and ending at an input/output point, is one of the main components of order-picking.

Among the methods developed to reduce a picker's travel distance (or time), assigning products to suitable storage-locations has been identified as an important way to improve the efficiency of order-picking [2, 3]. Consequently, in this study, we focus on the way order-picking can be improved by optimising the storing process and we provide more information on it in the next section.

2.2 The Storing Process

The storing process refers to the allocation of product items to storage-locations in a warehouse with the goal of reducing material handling cost and improve space utilisation [4] and has been found to reduce a pickers travel distance or time [2, 3]. The storage process has three main significant issues to cover [4]: (i) the quantity of a product that should be stored in a warehouse; (ii) the replenishment frequency a product-type requires; and (iii) the storage assignment of each of the product-instances in a warehouse. The first two problems belong to the traditional inventory problems referring to lot sizing and scheduling.

The storage-location assignment problem considers many issues such as the main storage-location decisions of allocating product-items to different storage-locations, the scheduling of inventory transfers between departments, allocating product-items to different zones and assignment of products in a storage-location within a zone [4]. This study focuses on the main storage location problem of assigning products to different storage locations. A detailed review of and comparison between different available storage policies can be found in [10].

3 An Adaptive Strategy for Storage Location Assignment

3.1 Suitability of Product Intelligence

The storage policies presented in the previous chapter locate entire products from scratch [5]. An alternative to this is an approach that calculates the optimised storage location of newly arrived items, based on the current status of the warehouse and the historical data at the time of arrival. Currently, there is only limited research on adaptive storage assignment policies and the way they can improve a warehouse's performance [5]. A general description on the way an adaptive storage policy could be realised in a warehouse environment can be seen in Fig. 1.

Once an item enters a warehouse, its type has to be identified often using an automated identification technology such as barcode or RFID. In a non-adaptive policy, the product type should point to a pre-assigned storage location for the newly arrived item. In an adaptive policy, the item needs to access historical data regarding its turnover rate, order frequency, class etc. and decide on the best location to be stored. In order for this decision to be made, the warehouse manager

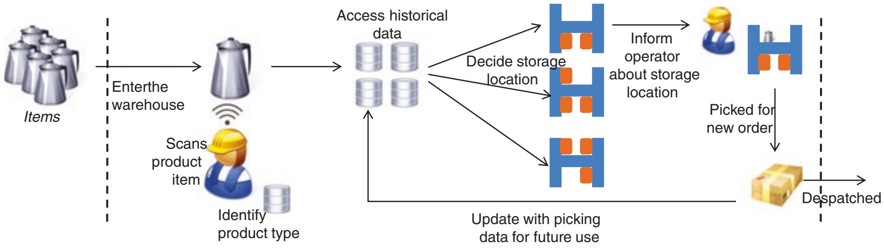


Fig. 1 General description of an adaptive storage policy

might need to collect information about the availability of storage locations at that particular point of time and perhaps follow some form of iterative procedure in consideration of the storage needs of other incoming items; i.e. the best storage location for any one product may be compromised by the storage needs of other products. After the decision is being made, it has to be communicated to a human operator which will sort away a number of items using a picking device. Finally, whenever the item is picked for a new order and is prepared for despatch, the item needs to update the historical data of its product type for future use.

The product intelligence paradigm [11, 12], as an approach that treats different product instances specially, could be, on face value, a suitable solution for the deployment of such an adaptive policy. Intelligent products possess a unique identity (at the level of aggregation decided by the user) which can be used to identify and track a new product instance while it is sorted away, stored and packed in the warehouse. They are also capable of collecting and storing information about themselves or about similar products, which in this case refer to order frequency and turnover rates, physical dimensions, distance travelled during picking etc.

Their communication and decision making capabilities can be used for the specification of their storage location, perhaps after interacting/negotiating with other items of the same product type, other competing newly-arrived items or the shelves and racks in a warehouse. Finally, product intelligence requires a language to display a product's decisions to warehouse operators that can execute any decisions made in the physical world by storing a product in a specific storage location. The decision making process and the agent interactions in the context of this study are discussed in the next section.

3.2 *Deciding the Storage Location*

In this section we describe a storage location strategy based on the product intelligence paradigm, in which products and warehouse are treated as interacting agents. This strategy aims to minimise the travel distance a single product needs to cover from its storage location to the depot when requested in an order. The strategy developed consists of two main elements. The first element is a set of

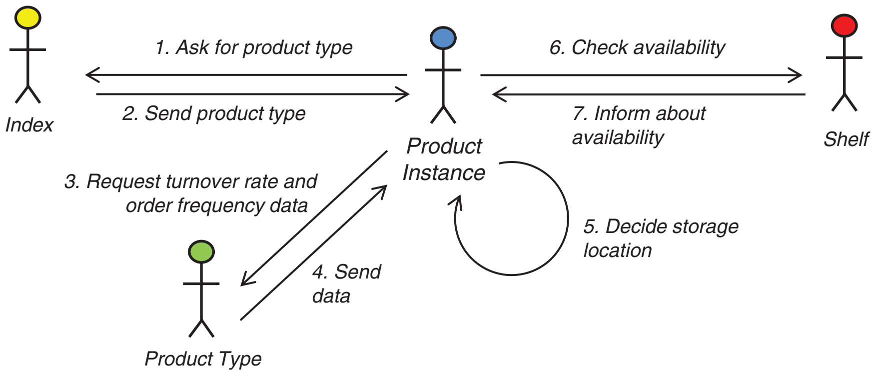
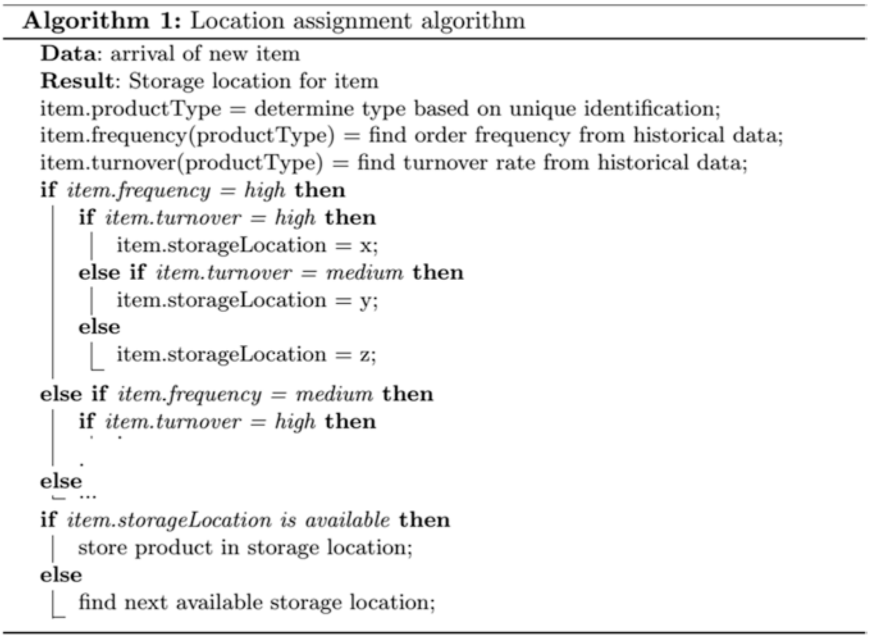


Fig. 2 Agent interactions

interactions, between a product agent representing a newly delivered product and three different warehouse agents, that allow the product to collect information to be used for identifying the new storage location. These interactions are visually depicted in Fig. 2. Even though, at this point, an agent representation of all different entities (product instance, index, product type and shelf) might not be necessary; the system has been designed in this way in order to be able to accommodate future extensions more easily.

The second element is an algorithm followed by the item to decide its storage location. The algorithm is based on two variables, namely order frequency and turnover, and should remain adaptive to customer demand.



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Algorithm 1: Location assignment algorithm
  Data: arrival of new item
  Result: Storage location for item
  item.productType = determine type based on unique identification;
  item.frequency(productType) = find order frequency from historical data;
  item.turnover(productType) = find turnover rate from historical data;
  if item.frequency = high then
      if item.turnover = high then
          item.storageLocation = x;
      else if item.turnover = medium then
          item.storageLocation = y;
      else
          item.storageLocation = z;
  else if item.frequency = medium then
      if item.turnover = high then
          . .
      .
  else
      ...
  if item.storageLocation is available then
      store product in storage location;
  else
      find next available storage location;
```

Order frequency shows the number of times that a product has been ordered and as a result the number of times an operator needs to pick that product. Turnover refers to the order frequency multiplied by the price of the product-item, which shows the importance of the value per product as well as the value that has been added to that product. Generally, order frequency is a more significant factor than turnover regarding a storing policy that aims at minimising the travel distance of picking. The resulting algorithm is presented above. Notice that the higher the order frequency the closer to the depot the storage locations assigned will be (similarly for the turnover rate).

The algorithm is used by each product instance, every time they enter the warehouse, using information up to date thus making the strategy adaptive. In case of fluctuations in the product demand, the product will be aware of that through historical information and will be stored in a different area in a warehouse. Even though adequate time will be needed to influence the picking performance of the warehouse, no reshuffling of stock is required in the warehouse. Product intelligence is the key characteristic of this algorithm. Product-items have information about their order frequency and turnover of the previous month and can be allocated in a different area from the next month on till there is a new change in their information (which will rank the items in a new area after comparing their information with the one of the rest of the products). A further development would allow for the simultaneous arrival of multiple orders.

4 Case Example

4.1 Operational Context

The company used as a case study for this paper is an eCommerce order fulfilment warehouse. The company warehouses, picks, pack and dispatches goods to end-customers on behalf of their clients, the retailers. The reader is referred to [6] for more information on the company's business challenges and needs and the opportunities arising from using product intelligence in their operations. In this section we focus on the storing process.

The company is currently using a random storage policy. In the random storage policy, every incoming product is assigned to a storage-location in the warehouse, which is randomly selected from all empty locations with equal probability. This policy leads to high space utilisation, but also increased travel distance [13]. The only criterion of random storage strategy is to allocate the product to an available shelf [5]. However, a pure random storage policy will only be possible in a computer-aided environment that can calculate the equal probability of each storage-location. In practise, the order-pickers are the ones who choose the storage-location randomly, which was also observed in the case company. According to this policy, the pickers choose the first empty location that is available to store the products. This often results in a warehouse with full racks around the depot and gradually empty towards the directions away from the depot [2].

This storing strategy has been chosen since the company cannot know in advance the specific products they will receive each day from their clients as well as the point of the day they will receive them at. As a result, the usage of static algorithms that determine new storage locations for incoming product instances before the beginning of each working day is not practical. At the same time, the company believes that although zoning the warehouse could reduce the overall picking time, these zones will need to change very often (since the demand they are facing is volatile), thus creating confusion for the staff members.

4.2 Design of Simulation Experiments

The simulation software selected for this study was SIMIO, a simulation modelling framework based on intelligent objects [14]. Four factors are studied:

1. *The storing policy*: random or adaptive (described in the previous section)
2. *Fluctuation of demand*: dynamic demand, which changes every month, and stable demand that stays the same throughout the experiment
3. *Storage location length*: the current value in their small warehouse (1 m), the value of the standard size of a pallet used in their big warehouse (1.5 m), the value of bigger storage-locations, used by other warehouses (2.5 m)
4. *Distance from the warehouse to the packing stations*: the current value of the company's warehouse (30 m) a shorter distance (5 m), and a theoretical distance that allows as to focus on the picking process inside the aisles (0 m). The company operates a rectangular warehouse with one depot.

4.3 Results

Figure 3 compares the random policy currently used by the case company against the adaptive strategy in terms of the average travel distance savings per item. We can see that an adaptive strategy has reduced the travel distance by 3.95 % (5.8 % in the current warehouse) but its benefit can be much higher in warehouses with larger storage locations and depots closer to the storage area. In particular, we notice that the results of the simulation experiments are significantly affected by the current warehouse layout, in which the distance between the storage locations and the depot is too long. After leaving the storage shelves, the pickers will still have to cover a long distance to reach their depot. Thus any distance reduced inside the picking area will be very small proportional to the total distance travelled. This is why, when we focus on the picking area only (distance = 0 m) the total benefit exceeds 20 %.

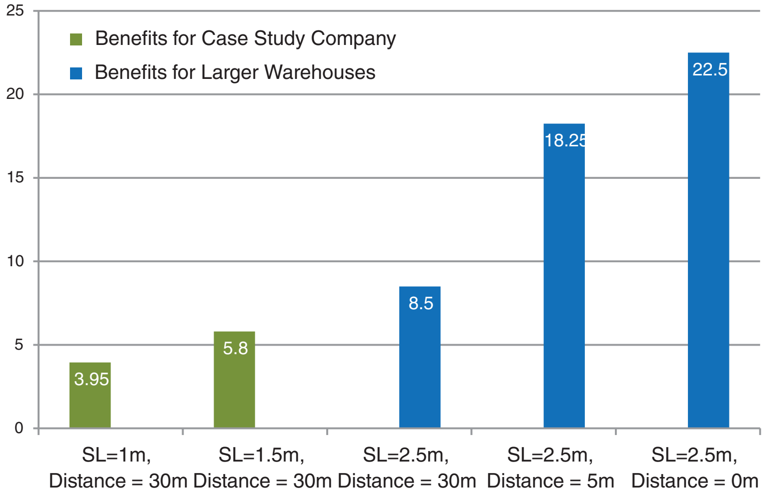

Fig. 3 Benefit of average travel distance per product-item for dynamic demand (%)

In a similar way, we studied the adaptability of the strategy in cases of dynamic demand. More specifically, the figure compares the average travel distance achieved using the adaptive strategy under stable demand with the case of dynamic demand. Here, the differences are much smaller; however, it is shown that the strategy can indeed deal with changes in demand, achieving similar levels of service. Once again, the distance between the storage locations and the depot plays an important role. More details on these results can be found in [10].

5 Conclusions

In this paper, we have presented an adaptive strategy for the storage-assignment problem aiming at minimising the travel distance of the human operators during the picking operation. The strategy's goal is to provide an improved storing policy that can cope with the fluctuating demand faced by warehouse organisations today. The initial results show a benefit on the average travel distance per item that reaches 22.5 % inside the picking area of big warehouses. The strategy was also inspired by the principles of the product intelligence concept which can also facilitate the deployment of such an adaptive strategy. Further investigation is required for the understanding of the benefits of such a strategy, taking into account orders with multiple items, pick-cycles with multiple orders, more than one human picker and more frequent demand changes.

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Open Tracing Container Repositioning Simulation Optimization: A Case Study of FMCG Supply Chain

Shenle Pan and Eric Ballot

Abstract The industry and retail chain use a huge number of low cost assets such as pallets, crates, plastic boxes… Until now the lack of affordable technology, in comparison with the cost of a single asset, stopped efforts to manage them in open loop supply chain (where the assets are not coming back to the sender after usage). As part of a project to implement an affordable and efficient communication technology and to publish the information from the logistics assets used in Fast Moving Consumer Goods' supply chains, we demonstrate with a simulation optimization approach the benefit of knowing the position of the assets. The published events from the logistics support are used to optimize their repositioning. A specific simulation optimization model is presented and the results are commented.

Keywords Coupled simulation optimization model · Open tracing container · Repositioning problem · Internet of things

1 Introduction

Logistics supports and containers are managed in several ways depending on information available and business models: rental, pooled etc. When one focuses on pallets, crates or small containers, the cost of information tracking is too expensive to enable individual management regardless of the huge number of support means used by the industry. One solution is to manage reusable logistics support in closed loop (return to sender after usage), as done by the automotive industry since decades, but this is far from optimal. The state of the art in supply chain management is now more oriented towards pooling and interconnection of logistics services, thus

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S. Pan (✉) · E. Ballot
MINES ParisTech, PSL Research University, CGS—Centre de Gestion Scientifique,
60 Bd St Michel, 75006 Paris, France
e-mail: shenle.pan@mines-paristech.fr

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open loop. We propose here a framework to optimize the repositioning of Open Tracing Container (hereafter OTC) based on information captured by mobile RFID readers and information publication, thanks of EPCglobal[1] emerging standard [5]. The availability of individual information in open loop supply chains enables new organizations like Physical Internet [1, 9], where optimization and comparison with business rules were used before in the studied case of fast moving consumers goods.

This paper is based on the result of an applied research project in France. The main objective of the project is to study the possibility and feasibility of applying the OTC in the Fast Moving Consumer Goods (hereafter FMCG) chains in France. In this paper we exclusively focus on a part of the project that is the supply and repositioning optimization problem of OTC in the open network using a model coupling simulation and optimization tools. The model is applied to a real world case study to assess the performance.

The paper is organized as follow. After introduction, in Sect. 2 we will present the concept of the OTC and the objective of this paper. In Sect. 3 we present a general introduction to justify the need of simulation optimization model. In Sect. 4 we present the construction of the model and its application to a real word industrial case of FMCG chains, in order to validate the model and assess its performance. Section 5 is the conclusion of the paper.

2 Application of Open Tracing Container in FMCG Chain

2.1 The Need and Usage of Individual Traceability

Shipments are becoming more and more fragmented [4]. As a consequence, the dedicated supply chain is more and more challenged by open solutions. Maritime containers, the Physical Internet [1] or logistics pooling [10] are three examples of this trend in these shared logistics network; there is an increasing need not only for traceability but also for the management of the network itself. While the maritime is a very specific environment allowing huge budgets for traceability and security, the inland logistics still requires specific and affordable solutions. Especially the context of the Physical Internet (PI) requires new solutions for systematic traceability and management of reusable logistics containers.

2.2 The Concept of Open Tracing Container

The Open Tracing Container named hereafter OTC is a concept used in the *OTC KayPal®MR* project[2] to represents any FMCG logistics support designed for

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[1] www.gs1.org/epcglobal.

[2] http://www.4snetwork.com/activite/produits-services/otc-kaypal-mr/.

open supply chain, within the scope of Internet of Things [6]. As we do not know yet the final form of PI containers, even though Lin et al. [7] and Ballot et al. [1] give an early study on the size of PI container, we use here a cardboard layer pallet to emulate it. The cardboard pallet is based on a commercial product made by DS Smith Packaging[3] KayPal®. This product has the advantage of being lightweight and used as a layer pallet (an intermediate between pallet (floor) and a cardboard box), thus a good approximation of the PI container medium size in FMCG.

For the sake of the project the OTC is equipped with a passive RFID tag and the information is published by Orange in a computing cloud environment according to GS1 EPCglobal standard [5]. The EPCglobal standard enables direct publication to the Internet of all events captured from operations in a context enriched and a protected framework.

The OTC is manufactured and shipped to industrials of the FMCG supply chain. The industrials use pallets with several OTC to prepare the shipment to the retailer. The retailer uses them to store and prepare orders to shops—with other logistics supports (pallets or rolls). The OTC are then collected, concentrated, inspected, sorted and shipped back to the closet industrial for a new loop or scarped. The cardboard pallet is thus a very good approximation of an OTC and part of functions required for a PI-container while in the same time compatible with current FMCG logistics practices.

2.3 *Objective of the Project and Contribution*

The *OTC Kaypal® MR* project funded by BPI in France has several aspects and objectives as follow, see also [6]:

- Demonstration of feasibility: are the technologies mature and reliable enough for logistics use? Is the cost affordable?
- Validation of EPCglobal implementation in an open environment with different partners (industrials, carriers, retailers, logistics services providers and IT services providers)?
- Interest: what will be the value of the individual information at OTC level for OTC management and product traceability?

Our contribution explained here is to develop a simulation tool to represent the logistics network as it is with business rules on one hand and to develop a simulation optimization model to measure the interest of individual traceability and improvement margins on the other hand.

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[3] www.dssmith.com.

3 Simulation and Optimization Coupling Approach

This part introduces the model of coupling simulation and optimization that was developed in the research project. Only the conception and function of model are illustrated here. All details concerning configuration and formulation of the model related to the real situation will be presented in the part of case study.

3.1 Brief Literature Review

The approach of coupling simulation and optimization, also called hybrid simulation-optimization methods in [3] or combinatorial simulation-optimization in [11], is a method adequately used for optimization problems. Carson and Maria [2] give the first discussion providing a critical review and application of the method. Recently Figueira and Almada-Lobo [3] give an in-depth study of taxonomy and discussion on this method. In general, the idea is to couple the simulation and the optimization tools or approaches to build up a closed loop system. For example, the results (the output) of optimization serve as input data to the simulation model; and after processed the output of the simulation model will be used as the input data for the optimization model at the beginning of the next step, see Fig. 1 as an example.

The method has been applied in different fields to resolve optimization problems in the literature. Zeng and Yang [12] use the method to develop a specific model for a scheduling loading operations problem in container terminal. Rytwinski and Crowe [11] develop a decision support system under uncertainty based on a coupled simulation-optimization model, for a problem of optimizing fuel-breaks location to minimize expected losses from forest fires. With the same idea, [13] employ simulation model to evaluate the performance of optimization results under a stochastic environment in ambulance deployment and relocation problems.

From the literature we can observe that the simulation-optimization approach is usually employed for two objectives: decision making via optimization, and performance evaluation via simulation (under stochastic or uncertainty environment for example). The approach is similar; however a specific model is necessary to resolve a specific problem.

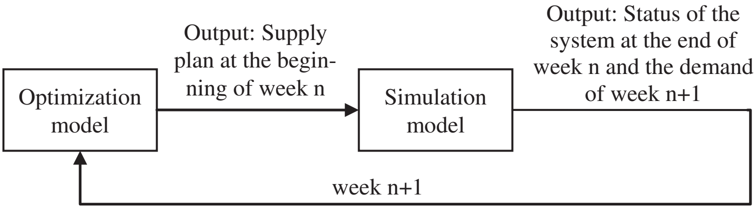


Fig. 1 The proposed closed-loop continuous time simulation optimization model

3.2 Closed-Loop Continuous Time Simulation Optimization Model

Inspired by the studies in the literature, in this paper we develop a specific hybrid model adapted to the supply and repositioning optimization problem of OTC in a semi open network. Basically we use a model to simulate the movement of containers in the network subject to the real configuration and behaviour of the network, in order to assess the performance of different assumptions by comparing the Key performance Indicators (KPI).

This is a continuous time simulation model and at the beginning of each period (i.e. week) it should make decisions on the supply and repositioning plan (quantity and path) according to the coming hebdomadal demands of container in the network. Thus, it is a closed-loop continuous time simulation optimization model, as shown in Fig. 1

4 The Case Study

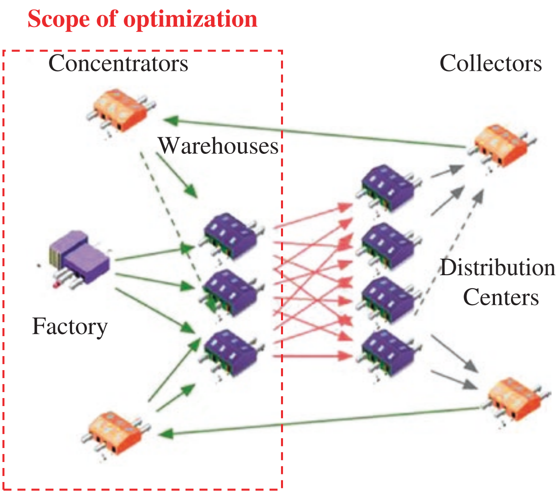
4.1 Problem Description

A case study was conducted to assess the perspectives of application of open tracing container (OTC) in FMCG chains. As said, we focus here only on the supply and repositioning optimization problem, thus the simulation optimization model.

The real life case is based on a national supply network in France containing one factory of OTC which is the ultimate supply source, 5 concentrators that are the sites of repositioning and the stocking points of OTC, 23 collectors that regularly collect OTC from retailers, and 6 warehouses of suppliers that serve 43 distribution centres of retailers with the use of OTC, as shown in Fig. 2. The red arrows in the figure represent the demands of OTC on the basis of the shipments from the warehouses to the distribution centres that are real data from industries. However, the project is still running and flows, therefore location of sites and other confidential data cannot be presented here. Note that we use the same input of shipments as well as the demands in all scenarios of simulation. Therefore the comparison of simulation results is legitimate. The other arrows stand for possible paths for supplying, repositioning and collecting OTC. However, only the flows of supply or repositioning are considered in the optimization model.

A real database containing 30 weeks' flows from warehouses to distribution centres is provided by the industrial partners in the project, as well as the detailed business rules of all sites (demand and holding time on site, the time of collecting and scrap rate of OTC etc.). All these rules are taken into account in the simulation model in order to correctly describe the case.

Fig. 2 The case of supply network with the use of OTC



4.2 Model Construction

In the presented case, we model the problem by using WITNESS[4] for the simulation model and Frontline Excel Solver[5] for the optimization model. To couple the independently constructed models, we adopt the Object Linking and Embedding (OLE) Automation that is well known as an inter-process communication mechanism. The main reason is that the optimization Solver is embedded in Microsoft Excel where we can develop a Macro program to control and coordinate the simulation and the optimization model. Since the Macro program is relatively simple we will focus on the models in this part.

Design of the simulation model

A discrete-event simulation model is developed upon the WITNESS platform. Due to the limited space the entire simulation model is not presented here. The reader can refer to Markt and Mayer [8] for an introduction to WITNESS and the deliverables of the project for more details (see Footnote 2). As said the simulation model is used to simulate the OTCs' movement during 30 weeks in the network shown in Fig. 2 and to export output data to an Excel file at the end of each week. Meanwhile the simulation should respect the real behaviour of sites and flows, i.e. the business rules as follow:

- *Factory*: serving as an infinite source of new OTC. Shipments from factory to suppliers' WH are once per week in every Monday morning according to weekly supply plan.
- *Concentrators*: the 5 concentrators are the stocking points of used OTC, where to scrap the damaged OTC. They have the same shipment

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[4] www.lanner.com.

[5] www.solver.com.

behaviour as factory, but the inventory level could be different. In particular, one decision to be made is to supply new or used OTC from which site with what quantity on the basis of real time inventory level and assumptions, see the scenario analysis part.

- *Collectors*: the 23 collectors serve as OTC consolidation centres in the middle of retailer DCs and concentrators. A DC will be served by the closest collector. As input rules, the collection frequency as well as the day is predefined for each DC: once a week or every two weeks possibly from Monday to Friday. All collected OTC are shipped to the closest concentrator at the end of week.
- *Warehouse (WH)*: at the beginning of each week and before establishing the weekly supply plan, each of the 6 WH (of suppliers) calculates the demands of OTC for the coming week according to the on-hand stocks, then sends the orders to planner (of factory or concentrators). Then, the WH will fulfil the real shipment to DC during the week on the basis of the real data, and with the use of OTC. Recall that the input data of shipments and demands is the same to all scenario of simulation.
- *Distribution Centres (DC)*: the 43 DC (of retailers) are the places where the goods will be stocked as well as the OTC. As input rules, the holding time is different in each DC and it depends on the inventory turnover of site (from one to three weeks). In particular, collector cannot collect an OTC in stock.

All real-life rules defined above are considered and modelled in the WITNESS discrete-event simulation environment. As said, supply plan is the only decision to be made within the simulation. Two scenarios are defined to compare the performance of different decisions, as well as to validate and verify the simulation model. The first scenario is simulating the current supply rules (which can verify and validate the simulation model via KPIs), and the second is optimizing total the transportation distance and global inventory level when establishing a supply plan, see Sect. 4.3 for details of scenario design. Now we present the optimization model of the second scenario.

Design of the optimization model

Since the simulation model cannot meet the objective to establish an optimized OTC supply plan in terms of transportation or inventory for example, an optimization model is thus needed. The model is constructed in Excel with Frontline Solver, which is powerful and efficient for Linear programming problems. In this case, the optimization problem of supply plan is formulated as follow.

Assumptions

- The capacity of trucks is 952 OTC/truck (due to practical issues);
- To optimize the transportation, shipments from factory or concentrators to WH are always in Full-truck-load of 952 OTC;
- All weekly demands of OTC from warehouses should be satisfied;
- A WH can be supplied by more than one concentrators and the factory.

Notations

- f: the factory f;
- i and c: WH i, i ∊ I the set of WHs; and concentrator c, c ∊ C the set of concentrators;
- d_{ci} and d_{fi}: distance of path from c to i and path from f to i;
- n: week n and n ∊ N the set of weeks;
- DE_i^n: OTC demands of WH i for the coming week n
- ST_i^n: on-hand stock of WH i at the beginning of week n (before planning);
- ST_c^n: on-hand stock of c at the beginning of week n (before planning);
- FL: full-truck-load of 952 OTC;

Decision variables

- Q_{fi}^n: number of shipments (of FL) from f to i of week n;
- Q_{ci}^n: number of shipments (of FL) from c to i of week n;

$$\min \sum_{c\in C;i\in I} Q_{ci}^n \cdot d_{ci} + \sum_{i\in I} Q_{fi}^n \cdot d_{fi}; \quad \text{for } \forall n \in N \tag{1}$$

s.t.

$$Q_{fi}^n \cdot FL + \sum_c (Q_{ci}^n \cdot FL) + ST_i^n \geq DE_i^n; \quad \forall i \in I, \ \forall n \in N \tag{2}$$

$$\sum_i (Q_{ci}^n \cdot FL) \leq ST_c^n; \quad \forall c \in C, \ \forall n \in N \tag{3}$$

$$Q_{ci}^n \text{ and } Q_{fi}^n \text{ are integers} = 0, 1, 2 \ldots N \tag{4}$$

$$Q_{fi}^n \leq \max(0, \left\lfloor \frac{DE_i^n - ST_i^n - ST_c^n}{FL} \right\rfloor \ \textit{for } \forall c \in C), \ \forall i \in I, \ \forall n \in N \tag{5}$$

It is a Mixed-integer linear programming (MILP) optimization model for a single-period single-commodity network flows problem. The objective function is to minimize the total transportation distance from factory or from concentrators to WH for a given week n. Constraint (2) ensures that weekly demand of each WH should be satisfied (with consideration of the on-hand stocks of WH). Constraint (3) ensures that a concentrator cannot ship more OTC than its on-hand stocks (shipment of FL only). The decision variables that are the number of shipment of FL should be integer numbers, as constraint (4) defines. Finally the objective of constraint (5) is to minimize the global OTC inventory level. The constraint means a WH will be shipped by the factory if and only if none of the concentrators has enough stocks (up to FL) to satisfy the WH's demand. Without this constraint, a WH geographically close to the factory will be always served by the factory. It means more and more OTC are injected in the system and the final result is a very high inventory level of OTC.

4.3 Results and Scenario Analysis

The simulation optimization model has been run on ThinkPad W530 with Intel Core i7-3940XM (3.8 GHz) and 32 Go RAM. It took a couple of hours to finish the simulation for 30 weeks. For the sake of accuracy, the outputs of the first and last weeks are not considered in the analysis (to wipe off the influence of the initial stocks and the incomplete flows of last week on the result). Thus the results presented below are based on the output of 28 weeks of simulation. As said, two scenarios were defined:

- **Scenario 1** is based on the current supply rules: each WH is supplied by the closest concentrator or by the factory if the assigned concentrator has not enough on-hand stock to satisfy the WH's demand. Actually the simple and intuitive rules partly optimize first transportation distance and then inventory level. But no optimization model is needed in Scenario 1. Besides, the constraint of FL shipments only is maintained to the flows factory—WH and concentrator—WH in Scenario 1
- **Scenario 2**: the decision on supply plan will be made with the help the optimization model that optimizes the inventory and transportation at the same time.

Some KPIs are defined and used to illustrate the results and compare the scenarios, see Table 1. The results presented in the table as well as the models were verified

Table 1 KIPs of simulation results of 28 weeks

KPI	No. Sc	Average	Max	Min
1. Average weekly transportation distance (KM)	Sc1	64,943	98,606	36,522
	Sc2	65,034	98,495	36,576
2. Average number of rotation per OTC	Sc1	1.6	6	1
	Sc2	2.38	8	1
3. Average days per rotation of OTC	Sc1	57.35	119	7
	Sc2	26.17	91	7
4. Average KM per rotation	Sc1	665	1,894	30
	Sc2	719	2,024	40
5. Average weekly scrap rate (scraped OTC/total OTC)	Sc1	1.77 %	3.88 %	0.48 %
	Sc2	3.81 %	9.80 %	0.67 %
6. Average daily global inventory level	Sc1	22,600	31,658	11,018
	Sc2	11,957	13,793	10,477
7. Average daily inventory level of WH	Sc1	3,971	6,968	1,642
	Sc2	3,921	6,968	1,642
8. Average daily inventory level of DC	Sc1	3,161	4,778	1,340
	Sc2	3,168	4,778	1,441
9. Average daily inventory level of collectors	Sc1	719	4,485	0
	Sc2	708	4,485	0
10. Average daily inventory level of concentrators	Sc1	14,750	26,320	2,803
	Sc2	4,160	7,261	1,116

and validated by the partners in the project. However, as this is a pilot study of a project to assess the practicality of OTC in real world case, only results of the OTC-based scenarios are available. It is therefore impossible to compare the scenarios with or without OTC. In terms of transportation, the two scenarios have nearly the same average weekly (and total) KM in transportation. However, their performance in other KPIs is very different. Regarding the rotation KPIs of OTC (one rotation of an OTC starts from its expedition form factory or from concentrator and ends by its return to the concentrator), Sc2 has obviously better performance on average number of rotations per OTC and average days per rotation per OTC. As a consequence of the objective to reduce global inventory level, the rotation of OTC has to be speeded up in order to meet the demands. Meanwhile Sc2 has slight increased the average KM per rotation per OTC due to the constraint (5) in the optimization model. Sc2 has also a higher scrap rate because in this scenario there is less new OTC injected to the network (used OTC in stock have priority). Concerning average daily inventory level, Sc2 has clearly reduced the global inventory level thanks to the reduction of inventory at the level of concentrators, again, in virtue of the optimization model.

However, the two scenarios should have the same daily inventory at the level of WH, DC and collection, since their inventory depends on the FMCG flows and the collection frequency that are the same in the two scenarios.

5 Conclusion

In this paper we study a supply and repositioning optimization problem of open tracing containers in the context of an open loops FMCG network. A model coupling simulation and optimization has been designed to resolve the problem. Considered as a decision-making tool, the model has been used in a research project studying the possibility and feasibility of using the *OTC-KayPal*® in the FMCG chains in France. In this project, with the proposed model we demonstrate the value of individual tracking to optimize repositioning of OTC. The project as a whole is still underway and we expect other benefices for real operation tracking such as fewer losses and better visibility. Therefore it is too early to say if the OTC pallet will benefit from the model presented here. However this project is another step that shows the interest of tracking technologies in an open environment, thanks to new information capturing devices and publication standard independent of partners.

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A New Framework for the Management of Returnable "Containers" Within Open Supply Networks

Yann Le Roch, Eric Ballot and Xavier Perraudin

Abstract New logistics models—physical internet, pooling, control towers, reusable containers management—require an item-level traceability of physical shipping units that is independent of the partners involved in the supply chains. Current information systems architectures match this need by interfacing heterogeneous systems with each other. Such architecture can't meet the challenges brought by new and shared logistics models. We demonstrate here how the recent EPCglobal® standards and related technologies are settled in a multi-firm open network, applied to the management of reusable pallets, taken here as demonstrators of Open Tracing Containers (OTC). Materials and methods for capturing data and structuring information are proposed and implemented in the Fast Moving Consumer Goods flows. Results illustrate the reach of that "Intranet of things" prototype, leading to interoperable logistic services, throughout various levels: from identifier tag level up to the piloting of each partner's logistics networks. We highlight limits and perspectives in terms of technical track and trace solutions and assets management in this environment.

Keywords Electronic product code · Traceability · Returnable transport items · Standardization · Open loop tracking

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Y. Le Roch (✉) · E. Ballot
MINES ParisTech, Centre de Gestion Scientifique (CGS), PSL Research University,
60, Bd St-Michel, 75006 Paris, France
e-mail: yann.leroch@mines-paristech.fr

E. Ballot
e-mail: eric.ballot@mines-paristech.fr

X. Perraudin
e-mail: x.perraudin@4snetwork.com

Y. Le Roch · X. Perraudin
4S Network, 16 av. Chateaupieds, 92500 Rueil-Malmaison, France

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1 Introduction

Logistics, as an activity committed to the management of physical flows requires specific information systems, adapted to the logistic models in place [20]. Whatever their complexity, those management models are necessarily backed by information systems for locating and inventorying items, assets and vehicles [5].

Thus, new logistic models, such as the physical Internet, pooling, control towers, collaborative management of returnable transport items, require item-level traceability all along the chain and with every involved partner. In fact, whether we deal with a returnable transport items (RTI) flow piloting activity or routing items through a physical internet network [2], shipping units are constantly consolidated and deconsolidated, so as to optimize shipping operations and therefore need to be traced and piloted at a fine-grained level, possibly item-level [1].

For that purpose, underlying information systems have to be as independent as possible from the actors involved, so as to limit barriers to entry to those organizations, optimize communications, and limit inter and intra-firm interfaces [6].

According to [7], implementing those information systems are usually done through three different modes:

1. Solutions based on specific interfaces, developed on a case-by-case basis.
2. Solutions based on proprietary choices [19].
3. Solutions based on inter-firm standards.

This third mode, solutions based on standards assume a relative convergence of involved parties and their codification systems. As an example, this implies a common identification of each shipping unit, and also that these data are shared and understood by all stakeholders for easier flows and coordination.

This being so, each party of the chain involved temporarily or permanently in those interconnected networks must obey the shared protocol. The corollary of such an opening of this information system is that one must ensure data protection. The collaborative model calls for more shared data [15] taking into account relevant data rights, facilitating transfer while respecting data and business confidentialities. Then, this information and communication infrastructure offers to logistic partners a common and uniform approach to information that limits and even eliminates informational interfaces, fostering collaborative logistic model information transfers [8, 16].

In terms of informational architecture, the flexibility and resilience of the model we aim calls for a distributed, modular and networked architecture [21]. Web technologies have this capability and can also bring another form of sharing of a non-proprietary communication network [17].

In the following section, we will present the various solutions developed in industry in this matter. In the next section, we describe and position our experimentation case, before detailing our results and their analysis. Before that, we outline our subject of experimentation: returnable transport items.

2 Problematic

2.1 Returnable Items Management's Specificities

The diversity and number of management systems in place multiplies asset tracking procedures and corresponding information interfaces. This complexity, combined to the fact that RTI activities are seen as peripheral, leads logistics parties to consider them as a factor of cost, lacking any added value, or as a commodity.

New logistic models are based on traceability systems where permanent localization of this logistic container can contribute to track directly or indirectly the items transported and the vehicles carrying those various logistics units.

For that purpose, many organizations have tested the use of RFID technology for their productivity claim. This bulk reading by radio frequency of items identifiers allows us to track items flows on any site equipped by RFID readers, and set their track. This capture of an identifier has to be further enriched, published and shared so as to be accessible and useful for any party of this chain. The EPCglobal® standard can assist this second part, by supporting complex inter-firm logistics information systems.

2.2 EPCglobal®, for RTI Tracking in Open Loops

Whether they are for rent (Chep, LPR, Pick & Go, JPR, iGPS) or exchange pallets (EPAL), many pool managers have attempted to use RFID to pilot their assets pool. Despite those many pilot attempts, very few pool managers have finally adapted those means for identification and tracking.

The advent of the EPCglobal® standard since 2005 [10], now supported by FMCG manufacturers and retailers through their common association GS1 allows a convergent and unified approach of codification in supply chains. It offers a complete set of standards: tag level, XML messages (called EPCEvents), reader protocol, EPCIS databases, and discovery services for Electronic Product Code (EPC) data. This standard sets a common "language" bound to address the principal aims of event tracking of object flows—assets or goods shipped.

Each object is then identified through its individual identifier: the Electronic Product Code (EPC code). To track them, logistics locations and vehicles must read this identifier and publish event messages at any equipped business-step: shipping, receiving, inventory, packing, controlling, and waste zone.

Those data are then published through the Internet on shared standardized databases, called EPC Information Services (EPCIS). Stakeholders have access and exploit those data for their own purpose or their client's, assets owners, whether we deal with a closed (proprietary) or open (collaborative) loop [3].

This new approach is an answer to logistic needs in terms of interoperability of pooling solutions, routing, RTI management and, more broadly, as one of the likely technical frameworks for the emerging “Internet of Things”.

2.3 The Kaypal® MR Case

In this paper we describe a large scale implementation of such infrastructure, applied to the management of cardboard pallets used as interleaving logistics supports for FMCG goods shipped from manufacturer to retailer’s distribution centres.

This product-service solution (the Kaypal® MR service) is commercialized by DS Smith since 2010. As the cycle in Fig. 1 describes, pallets commercialized through a pay-per-use formula are shipped to manufacturers, stored or cross-docked on retailers distribution centres and then recovered through the transport network. Supports are then sorted, aggregated for full truckloads repositioning towards manufacturer’s sites. At each step of this cycle, inventories inbound and outbound flows are declared through a dedicated web-service. Thus, the piloting of this pallet flow is fuelled by “declarative” data. The timeliness and accuracy (weekly and bulk) of that information have then a direct impact on the knowledge about this RTI pool, its location and availability for further operations. The current business model of this service is based on pool-level calculations: cycle times, rotation rates, loss rates are known at the scale of the whole pool.

Improvement of repositioning solutions, pool balance, impact and responsibility of each element of this RTI chain requires the tracking data to be produced in near real-time, on shared databases, automatically, at the item level. Moreover, as

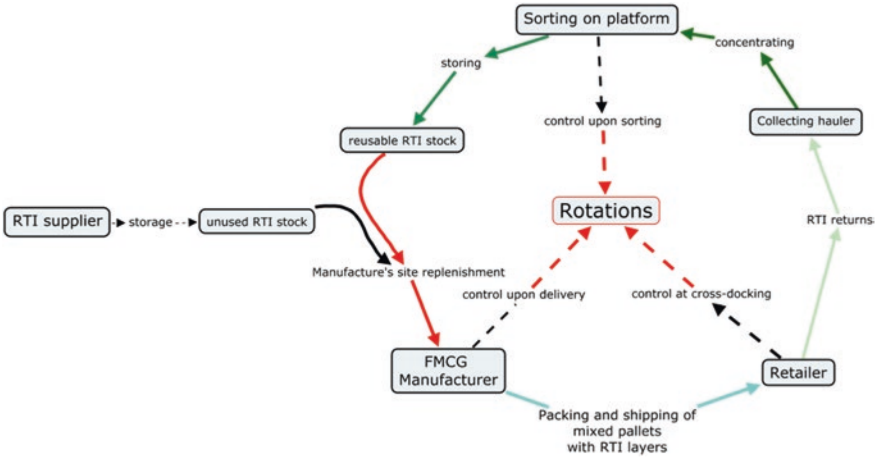

Fig. 1 The Kaypal® MR cycle

these RTI are managed through an open loop model, the envisioned information system needs to be as neutral as possible, so as to represent a new tracking layer.

The RFID capture of a pallet level identifier, published through an EPC-based information system was chosen as the technical background supporting this new approach. Our field of study, the Kaypal® MR service, is this product-service offer, were pallets are rented by DS Smith and physical flows piloted by 4S Network.

Our case study will help to illustrate the adoption of this EPC standard [18]. The organization that is equipped with this disrupting infrastructure is dedicated to piloting a pool of Kaypal® MR pallets, used by approximately one hundred FMCG sites in France: 15 manufacturers, 70 distribution centres, one pallet factory and 7 transport providers that are in charge of collecting and re-injecting those palettes in the cycle. Within this collaborative organization, active since 2010 and rolled out since 2011, we implemented the EPC Standard with corresponding RFID technologies so as to track those interleaving cardboard pallets.

The RFIDxEPCGlobal technological system limits the interfaces listed in the first part of this paper, and will foster the design of shared information systems, opened but nonetheless secured. Building on this standard, partners must design and implement fully interoperable solutions that are less dependent on the information system already in place in the chain: ERP, WMS, TMS, and EDI. Potentially, this standard could be one of the most appropriate frameworks for RFID tracking in open and collaborative environments.

Yet, before leveraging its full potential, many technological and organizational hurdles have to be solved.

3 Materials and Methods

The Open Tracing Container aims at designing a new RTI management model based on the EPCGlobal standard. This long term project on 36 months involves 7 partners, bringing appropriate competences in line with the new stakes listed above: a logistic and management lab, a Telco firm and its RFID lab, an RFID integrator, software developers and GS1. GS1 advocates the use of the EPC standard for transport and logistics activities. The main author of this paper managed this project, called Open Tracing Container (OTC), on behalf of 4S Network and its client, DS Smith.

By this means, the experiment takes place on a RTI piloting service that has already been optimized since 2010 in terms of management of physical flows. We can then isolate the effect of the only new element to this system: The Open Tracing Container solution based on the EPC infrastructure.

This experiment started in October 2011 and ends in December 2014. Almost every pallet injected in the Kaypal cycle is now tracked through this OTC system, providing an accurate and real-time visualization of the 100,000 transport items tracked and of their content. The lifespan of this logistic asset is less than

24 months, and its mean cycle duration is 6 weeks. Thus, our experiment produces significant results as we can follow enough rotations and lifecycles. Moreover Kaypal® MR users have access to the OTC results and include them in their daily operations.

3.1 Materials

We trace each of those pallets thanks to a passive tag that is sticked automatically to every new pallet injected in the Kaypal® MR cycle. Pallets progression through the network is then read by 30 readers that are positioned on the cycle's strategic points, allowing to trace this physical pool individually and globally, and to assess the impact of client and logistic service providers sites on the pool.

RFID reading converted in EPCEvents is then published on a network of four independent EPCIS databases controlled by the roles of this chain: the pallets owner, the goods manufacturer, the retail chain distribution centre, the transport group and the RTI service provider. Information about the products (lot number, GTIN reference, SSCC reference) is also published in parallel by one of the manufacturer's sites on his own EPCIS database, allowing to jointly tracing pallets and their products. In short, each role in the supply chain controls its own dataset.

Data thus distributed inside this network of databases can then be accessed through queries (pull mode) or subscription (push mode). The access control to these data strictly depends on the access rights and application needs one owns. EPC data processing then occurs inside OTC-Pilot, a kind of middleware application that produces generic RTI management indicators that are then broadcasted through this layer to operational parties and Objects (products and assets) managers and owners.

3.2 Experimentation Method

3.2.1 Standard's Layers in Use

The EPCglobal® standard constitutes a common technological frame for the 6 types of stakeholders involved in the Kaypal® MR physical flow. Each layer of this system gets a serialized identifier: RTI get a Global Returnable Asset Identifier (GRAI) code, sites a Serialized Global Location Number (SGLN), goods their Global Trade Item Number (GTIN), shipping units a Serialized Shipping Container Code (SSCC); read points can also be identified by their Global Positioning System (GPS) position.

The first part of the GRAI code identifies the EPC-Manager, i.e. the owner of the tracked asset, the second part "Asset Type" identifies the reference of the RTI tracked: wooden pallet, cardboard, roll, etc. The serial number identifies each item (Fig. 2).

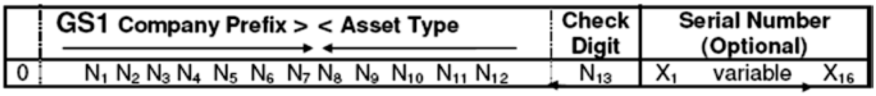

Fig. 2 The GRAI electronic product code structure

This information system infrastructure is rather homogenous as any layer is standardized or compliant with the EPC standard. Besides, reader software is coded for Android 4.0 OS, allowing this reading application to be used on smartphones, whether they are capable of RFID reading or not. The readers are piloted thanks to a COTS solution, provided by UBI solutions, a RFID integrator.

3.2.2 Reader's Type in Place

On the pallet factory site we use two fixed but light readers. Manual readers are used in other locations. These mobile readers are scanner-type readers on logistic sites, and smartphone-type readers. The latters are combined to a RFID antenna and used on board vehicles, where these smartphones are already in use for current transport activities. These choices suggest a trend toward the use of non-specific reading material that can include an EPCEvent's publishing software, among other smartphone-like applications. Publishing is done through actual communication networks: warehouse WiFi connections, offices WiFi connections, 3G accesses already used by haulers drivers. We then can leverage on the communication devices and networks already in place within actual supply chains.

3.2.3 Chosen EPCEvents and Complementary Declarations

Three EPC-Event types are used, depending on the expected granularity and the composition of the tracked unit:

- Quantity Events to declare quantities of objects (pallets).
- Object events when the EC GRAI codes lists are read through RFID.
- Aggregation events when those EPC lists are aggregated.

RFID-EPC captures are focused on strategic points of the RTI cycle: pallet tagging, truckload shipments of new or used pallets, goods packing, inbound and outbound movements. Extra readers are also used to track pallets collecting on distribution centres. By this means, one can visualize more thoroughly how many and which pallets are released out of the good's supply chain. Any RTI observation, coded in those EPCEvents can be combined with the declaration of the consignor or consignee sites those shipments come from, or are shipped to. Those voluntary declarations bring further visibility on physical flows upstream or downstream from the focal read point.

Our incomplete RFID coverage is therefore combined with declarative data. By this means, from the observation done on location and published, one can extrapolate on the previous or next location the objects are supposed to be.

This principle is dictated by the moderate value of the object tracked, which business model wouldn't stand a rather exhaustive and therefore expensive tracking infrastructure. This information structure combining ObjectEvents and QuantityEvents, proved to be well suited to our logistics environment, and is fully in line with the new version (V 1.1) of the EPCIS standard published in May 2014.

4 Results

This experimentation illustrates one way the EPC standard could be used within an open FMCG supply chain. The infrastructure settled is non-specific to the initial purpose: any EPC-identified object, site, client, asset, good… can be tagged and tracked through this system. As planned, this multi-purpose framework is characterized by limited specific interfaces: connection with a WMS and OTC data communication through email or web services.

This experimentation has produced three direct results:

1. *Tracking data* this data is mainly shared to optimize the RTI tracking service at the operational and tactic level. They are also combined to goods tracking data so as to design container/shipped goods traceability. By this new mode of traceability, information are published, treated and spread through the OTC network. In case of tracking alert, parties do not have to cope with too many interfaces and have a more standardized and direct access to track and trace data. This disrupts from the actual mode where data is accessed through a cascade of queries through multiple proprietary transactional data systems. This second work-package of the OTC project also illustrates the way an EPC-compliant infrastructure could be interoperable with current logistic information systems (ERP, WMS, TMS) of any of the chain partners. They communicate through XML messages communication or rather less sophisticated means: XLS files, e-mails. From September 2013 to November 2014 the OTC system has read, published and treated the circulation of more than 100,000 pallets, tagged at their manufacturer's premises, and then read all along their Kaypal® MR cycles. This data is representative of the whole flow of items as we almost tagged 85 % of the current active pool. Indeed, the reading rate of the flows both depends on the tag response (usually near 100 %) and this latter proportion of tagged items (here, over 85 %). Nevertheless, the readers in place proved to be capable of reading 99.99 % of a whole truckload (924 items).
2. *An OTC architecture* This architecture is designed to proceed to a first series of data processing of increasing granularity: from the object level to the shipment, up to the pool level. Logistic sites and service providers are also qualified and tracked.

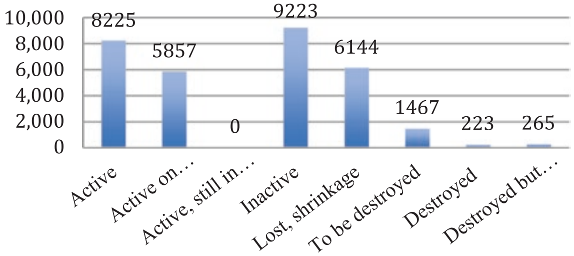

Fig. 3 Pallets sorting by the open tracing containers information system

3. *KPI* Our main RTI indicators are: each object's trace their performance (cycle count, condition, age, rotation speed) for any object and for the RTI pool as well, being it active or already scraped. Sites managing this physical flow are also assessed in terms of destruction rate, retention duration and also provider/client relations between the parties. At last, the RTI pool is sorted by condition: active, destroyed, inactive, loss, and by location (see Fig. 3).

In our case, 8 different states have been defined and calculated:

- Active, when pallets have been read within the RTI cycle in the last 6 weeks
- Active on transporter's site: (here 5,887 units): read on a transporter's premises
- Active still in stock: not injected in the RTI cycle yet.
- Inactive: pallets that have not been read and tracked for the last 6 weeks
- Lost, shrinkage: not read for the last 12 weeks, likely to be lost or reused

Our results are consistent with the current Kaypal industrial dashboard, while being more fine-grained:

a. The number of cycles spans from 1 to 15 cycles recorded through RFID.
b. The duration of those cycles spans from 2 to 20 weeks.
c. The age composition is made from the individual track of 62,000 objects.

4.1 Results Exploitation

These item-level KPIs complete the current dashboard used to manage the pool. The item level tracking brings better and finer knowledge about the pool: distribution by age, cycle time, cycle count.

Once used by RTI managers and service providers, they allow further optimization of the extent network, extended and facilitated access to tracking data, movement anticipation and control, by means of shared or specific dashboards. The impact of this new framework on the actual Kaypal process is tested and validated from June to December 2014. From this point, one can prototype other EPC-based services: RTI fine tracking, networked goods traceability [13].

4.2 Expected Applications

Through a field study, we are now willing to expand the use of such a model. For that purpose, we run a field survey to better assess how this model could address other logistics organizations also focused on assets or supply management. Retailers, pool owners, manufacturers were interviewed. Next cases of application could be closed loops [12] as well as open networks. Results of this enquiry will be presented in a forthcoming paper.

5 Discussion

Beyond the operational results described above, the results of this experimentation illustrate how one can implement a prototype of "*internet of things*", or more precisely an "**intranet of things**" [14], where logistics objects and sites are traced and assessed through publications and EPC-data processing.

This renews our view on logistics assets, such that the pervasive shipping pallets or any other kind of container are identified at the finest level: the item-level. Thus, this rather commoditized asset gets a personal identifier and can then be a crucial asset in term of Event-based tracking. The once commoditized asset becomes a logistics activities "tracker", whether it deals directly with the RTI or not. We thus disrupt this "container's" very identity [11].

In terms of organization and information system governance, our findings highlight pre-requisite rules for Event-data access. We noted here that the EPC-manager—the one that has tagged the objects tracked—would have a privileged, but not exclusive access to most of the data. Nevertheless, other parties can decide not to give access to their readings of the EPC code occurring on their sites. In that case, contractual rules between parties would help to arbitrate and refine data access rules. These access control rules are set at the higher levels of the infrastructure: EPCIS, middleware or client application (here: OTC-Pilot). Yet, this crucial question remains open.

5.1 Experimentation's Reach

The new architecture tested by the Open Tracing Container consortium and Kaypal users has a networked, distributed, decentralized logic that helps OTC-users to get partly rid of the interfacing strain.

In the first place, this model does not aim at providing systems integration or application specificity. Therefore, a rather extended GS1 community could leverage this new OTC layer which brings flexibility, compared to more "proprietary" schemes like ERPs. Nonetheless, in the context of OTC-businesses development, a certain degree of integration has to be coped with, as we experienced while trying to design products EPC-based traceability. We then have to combine event to transactional data, with the help of the fourth type of EPCEvents: TransactionEvent.

In terms of deployment, the budget size of the Open Tracing Container (OTC) project had a real impact on technical and organizational choices that built the proposed framework. Here, data capture remains mainly done by manual scanning, aligned to the usual code-bars processes in place. We then have to cope with non-automatic and non-systematic reading by hand-held readers. By this means, we do not fully profit the advantages of RFID capture: no need for line of sight, bulk identifiers capture, automatic reading. At this stage of experimentation, the tracking solution we designed isn't fully EPC/RFID and still remains influenced by the dominant design's logics of identifier capture and classical data processing [4]. We here can see that the initial logistic scheme remains a strong driver of the—deterministic—proposed solution [9].

Nevertheless, the uncoupling of physical flows and their informational trace shows a real potential in terms of service design that is still unexplored, where the logistic model is fuelled with "fine grained" data, available anytime through a shared EPC infrastructure. This would help operations to better anticipate and control assets flows, and better design routing solutions. Joint knowledge of this flow and the assessment by scoring of cycle sites would also help to better manage the whole pool.

This OTC experimentation highlighted the potential of the third mode [7], presented in the introduction to this paper, serving new-style collaborative solutions. Although being focused on pallets tracking through their GRAI code, this framework also proved it can process other EPC codes, read separately or combined as aggregates: SSCC, SGTIN, and SGLN. This data pool is then exploited through initial piloting services or could be used through novel approaches in terms of product traceability, leveraging as such an extended functional reach of this RFID/EPC framework:

- Initial Kaypal® MR traceability services managed by the 4PL (4S network)
- Product traceability managed by a 3PL LSP
- Vehicle tracking by transport companies, their clients or data processing

The economies of reach we have discussed have already been tested on nearly one quarter of the Kaypal® MR sites. Building on those first findings, OTC project partners have already identified ways to further exploit the potential of this framework. This new layer acts as a business-enabler where, on the base of a common pool resource (data and IT modules) various services can be designed and combined, provided the parties have sufficient access to the elements of this new information system. In order to run those new models, logistic professionals need to cooperate with EPC specialists, in order to fine-tune their EPC-based information system. Software development, EPC expertise, readers' management and many other highly technical aspects have then to be understood and mastered. Thus, implementing a logistics "intranet of things" is not only a question of logistics competences, but has to involve IT and data mining specialists.

6 Conclusion

The findings about the use of the EPCglobal® standard in open environment to improve RTI tracking give a glimpse of the full potential of such an information and communication infrastructure, in terms of codification, capture, broadcasting and exploitation of item level data.

The new relation to the edition, repositioning, exploitation and business development announces a new type of governance for a more distributed, inter-firm information system, fostering information sharing within competitive supply chains experimenting new logistic models. Nevertheless, industrial scale applications are still to be designed, developed and used at a larger scale. Business and technical issues have to be solved, for supply chains members to leverage this framework's potential.

The next step will be to learn from this experience at several levels: data accuracy, RTI management improvement, economic feasibility and foreseen new business models enabled by this individual traceability.

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A Simulated Annealing Metaheuristic for a Rail-Road PI-Hub Allocation Problem

Faiza Walha, Sondes Chaabane, Abdelghani Bekrar and Taicir Moalla Loukil

Abstract In this paper, a rail-road π-hub allocation problem is considered. A set of π-containers must be transferred from wagons to outgoing π-trucks using the rail-road π-sorters. A simulated annealing metaheuristic is proposed and compared to an existing heuristic. The main performance objective is to minimize the distance covered by each container to arrive at dock destination. Different scenarios are constructed and tested to compare both methods.

Keywords Physical internet · Rail-road allocation · Heuristic · Simulated annealing

1 Introduction

Montreuil et al. [1] present the actual logistic systems as unsustainable economically, socially and environmentally. The way goods are transported is extremely costly, accounting for a significant fraction of the gross national product for many countries. We observe that the continental transport is dominated by transportation

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F. Walha (✉)
LOGIQ, Université de Sfax, Sfax, Tunis
e-mail: walha.faiza@gmail.com

S. Chaabane · A. Bekrar
University of Lille Nord de France, 59000 Lille, France
e-mail: sondes.chaabane@univ-valenciennes.fr

A. Bekrar
e-mail: abdelghani.bekrar@univ-valenciennes.fr

S. Chaabane · A. Bekrar
LAMIH-UMR CNRS, Université de Valenciennes, Hainaut et Cambrésis, France

T.M. Loukil
Faculty ofbusiness administration, Tabuk university, Tabuk, Saudi Arabia
e-mail: taicir.loukil@fsegs.rnu.tn

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on road, leading a high demand for truck drivers. Many truckers are nearly always on the road, with bad repercussions on their family life, and on their health. Finally from environment point of view, the stakes are also high. The target worldwide CO_2 emission reductions are on the order of 20 % by 2020 and 75 % by 2050 [2].

In this context, the authors express the goal to revert this situation: unlock significant gains in global logistics, production and transportation differently, enhance the quality of life of the different actors implied in the system and finally, reduce the global energy consumption and pollution. To reach these targets and to build an efficient and sustainable logistics system, the author introduced the concept of Physical Internet (PI, denoted π).

The Physical Internet (PI, π) is defined as an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols [3]. In this structure, goods are shipped in containers like data packets in the Digital Internet, where networks are connected using standard packets of data under the TCP-IP protocol. In [1], the authors proposed three key types of physical elements to exploit the Physical Internet: π-containers, π-movers (π-vehicles, π-carriers, π-conveyors and π-handlers) and π-nodes (π-transits, π-switches, π-bridges, π-sorters, π-hubs, π-composers, π-shops, π-bridges…). The mission of the π-hub is to transfer π-containers from the incoming π-movers to the outgoing π-movers. Efficient hubs and transit nodes should provide a quick and synchronized transfer of the π-containers. Ballot et al. [4] presented a specific road-rail π-hub which aim is transferring: containers from truck to train (“road-rail”) and vice versa (“rail-road”); and from a train to another train (“rail-rail”).

In this paper, the “rail-road” problem is considered: the π-containers must be transferred from wagons to outgoing π-trucks using the rail-road π-sorters. The main performance objective of the “rail-road” zone is to minimize the time to interconnect trains and trucks services. Allocation of the containers to the trucks is one of several issues that must be treated. The problem is to define the appropriate assignment of unloaded π-containers from the train to the available trucks.

This paper is organized as follows. In Sect. 2, the related works of classical rail-road problem are presented. Our considered problem is described in Sect. 3. A heuristic based approach is proposed in Sect. 4. A Simulated annealing algorithm is described in Sect. 5. Computational results and experimentations are exposed in section five. Finally a conclusion and perspectives are addressed.

2 The Classical Rail-Road Hub

The rail-road hub includes an intermodal freight transport which is used to exchange cargo. There are many kinds of intermodal freight transport: sea-road, sea-rail, road-rail, etc.

In [5], the authors presented a module of a rail-road terminal and distinguished six basic design parameters. Then they evaluated and compared different terminal designs. Bontekoning et al. [6] analysed 92 publications relating to intermodal rail-truck freight transport. These publications treat different problems of the intermodal rail-truck: the rail haul modeling, the number of terminals in network, the container terminal locations, the train scheduling and routing, the blocking problem, a.o. The authors assume that the intermodal rail-truck had to be improved by more standardization. So, using the physical internet logistic is helpful in the pursuit of standardization. Newman and Yano [7] developed a formal optimization represented approach to determine direct and indirect train scheduling and container routing decisions with various origins and destinations. Boysen and Fliedner [8] treated the yard partition problem where they determined the appropriate cranes areas. The authors developed an exact dynamic programming procedure to solve the problem.

The contribution of our paper can be highlighted in three issues. First a standard intermodal rail-road named rail-rod π-hub is used where the terminal design is predetermined: the containers, trucks and wagons size, the number of doors, wagons and blocks of trains. Second, conveyors are used to move containers with different sizes from trains to trucks (not only the crane). Finally an assignment problem is treated where containers should be affected to the "best" truck whereas the most of existing articles deal with other problems as mentioned previously.

3 Problem Description

The rail separates the π-sorters in two sections: the above section is devoted to load/unload containers from a train to another train. Then the below section is composed of two other sections: the left section "Sect. 1" is devoted to unload containers from wagons to trucks and the right section "Sect. 2" is devoted to load containers from trucks to wagons. Each of these sections is manipulated by blocks of 5 wagons. The distance between two trucks is 1 m or 1.25 m, so each wagon can be processed by 5 or 6 trucks. We suppose that the number of trucks per section is about 28 trucks (see Fig. 1).

When the train arrives at the π-hub, it carries a set of containers. In our study, every container is unloaded in the rail-road sorters and transferred to the docks. These containers can be affected either to a next destination or to a specific truck according to the nature of the container. The assignment of trucks to the docks must be done before the arrival of the train (the contents of wagons are known about 1 h before the arrival of the train).

This problem is identified and formulated as a Bin Packing problem [9]. Two objectives are chosen to be minimized: the number of used trucks and the distance covered by each container to arrive at dock destination. In [9], the first objective was addressed. In this paper the second objective is considered.

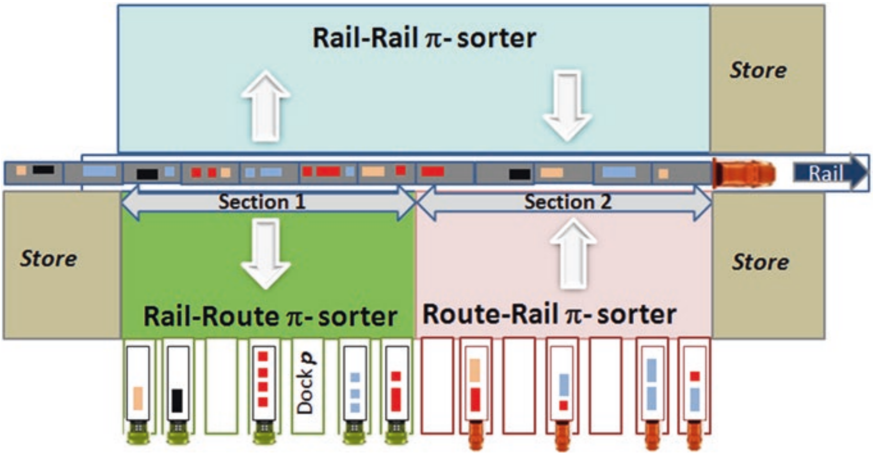

Fig. 1 Road-rail π-hub

4 Heuristic-Based Approach for the Rail-Road π-Hub Allocation Problem

In [9], a heuristic based method, named Best Fit Grouping Heuristic (BFGH), was proposed in order to find good solutions in reasonable time for the rail-road π-hub allocation problem. The solution obtained by BFGH will be used as initial solution for the metaheuristic in order to minimize the distance covered by containers.

The heuristic consists of four steps. The first step is for selecting randomly a destination not yet treated and determining all containers for the selected destination. In the second step, the containers are grouped satisfying the capacity/length of trucks in a set of groups $\boldsymbol{M_d}$ (set of groups of containers for destination d). In the third step, the solution obtained in the previous step is improved by the reassignment of the containers that minimize the number of used trucks. Finally, in the fourth step the groups of containers are assigned to the nearest dock according to the average position of containers.

The description and an illustrative example of the BFGH are detailed in [9].

5 Simulated Annealing-Based Approach to Rail-Road π-Hub Allocation Problem

Simulated annealing is a local search method that is able to explore the solution space stochastically and tries to escape from being trapped in local minima [10]. It is inspired from analogy to the physical annealing process of solids. SA accepts worse solutions in order to escape from local minima during its search using a probability which is decreasing by temperature. For a large variety of problems, the SA proves its efficiency to find good solution in reasonable time. SA is also simple to implement. For these reasons we choose to use it instead of other metaheuristics.

5.1 Notations

n	number of containers positions
M	number of docks positions
T	number of periods in the planning horizon
mid_i	position of the middle of the container i according to the axis of the containers delimited by the block rail-road
d_{ip}^t	distance covered by the container i at position mid_i to reach the dock p
T_0	initial temperature
α^t	coefficient to reduce temperature
N_T	number of iteration
$Sbest$	the best solution
$N(S)$	Neighbourhoods of solution S
ε	very small number

5.2 Algorithm: Simulated Annealing

Different versions of SA algorithms are defined in literature. For our problem, the following algorithm is proposed.

```
generate initial solution S
initialize
T←$T_0$
Sbest ←S
repeat
      i←0
repeat
      generate random solution $S' \in N(S)$.
      generate random number $r \in [0,1]$.
      if $r < e^{(\frac{f(S)-f(S')}{T})}$ then
        S←S'
        if $f(S) < f(Sbest)$
          Sbest←S
        end if
      end if
      i←i+1
  until i= $N_T$
  reduce T by the cooling schedule function
until $(T < \varepsilon)$
```

In the following, the different steps of the SA metaheuristic are detailed.

Step 1: Generate initial solution

The initial solution is defined by the BFGH heuristic.

Step 2: Create neighbouring solution

The defined groups are kept in current solution. To evolve this solution, three structures of neighbourhoods are considered:

1. First neighbouring solution is defined as follow: two docks are chosen randomly and their assigned containers and trucks are switched.
2. Second neighbourhood is obtained by fixing the docks in the solution obtained by BFGH and switching the containers.
3. Third neighbourhood considers the switch of the docks and the groups created in the initial solution.

The best solution obtained in these three neighbourhoods is maintained.

Step 3: Accept neighbouring solution

Finally, in the third step we must decide if we accept or reject the neighbouring solution. The acceptance of this solution depends on the probability p:

$$p = e^{\left(\frac{-df}{T}\right)} \tag{1}$$

where df is the difference between the current $f(S)$ (current best solution) and the neighbouring $f(S')$ solution:

$$df = f(S) - f(S'), \tag{2}$$

where $\boldsymbol{f}$ is the objective function of the problem (covered distance):

$$f(S) = \sum_{t=1}^{T} \sum_{p=1}^{M} \sum_{\mathrm{i}=1}^{n} d_{ip}^{t} \tag{3}$$

To reduce the temperature, we are using geometric cooling, with temperature at next iteration being set to $\mathrm{T} = \mathrm{T} * \alpha^{\mathrm{t}}$.

6 Experimentations and Results

The heuristic and SA metaheuristic are implemented in Java using a PC with processor Intel(R) Core(TM) i3 CPU 2.53 GHz and 4Go of RAM.

The two approaches are tested on randomly generated instances as follows:

- The number of containers $\boldsymbol{N}$ is chosen from the set {60, 90, 140},
- The number of destinations $\boldsymbol{D}$ is chosen among the values: {4, 6, 10, 15},

- For each container, its length is generated uniformly among the different possible lengths {1.2, 2.4, 3.6, 4.8, 6, 12}. The amount of containers lengths in a wagon should be less than the length of the wagon.
- For each container, a destination is generated uniformly in [1, D].

The SA parameters are defined as follow: $\alpha^t = 0.87$; $T_0 = 140$; $N_T = 100$; $\varepsilon = 140 * 10\ E - 6$. These parameters are fixed after some tuning tests.

Table 1 presents the results obtained by the heuristic and metaheuristic according to the criteria "covered distance".

The column "Heuristic versus SA" presents the improvement of metaheuristic results compared to BFGH heuristic. It is defined by: $\frac{BFGH-SA}{BFGH}$.

According to this column, the obtained results by SA are better than those obtained by BFGH. The improvement is around 5.5 %. We observe a maximum improvement of 10 % of gain in covered distance. This improvement is very important for the PI-hub, since for a good synchronization, containers should spend less time in the routing zone. By positioning the trucks in the best dock beside containers, the later covered less distance and spent less time to reach the destination docks.

On another hand, one notes that when the number of destinations increases, the average improvement is also increased. This can be explained by the fact that the increased number of destinations make the allocation problem harder, and the heuristic is less efficient. In this context, the metaheuristic makes better improvements.

The BFGH heuristic takes few seconds to reach the solution. According to the column "SA CPU Time", the metaheuristic takes more time to find results but it does not exceed few minutes (118 s in average).

Table 1 Results of BFGH and SA metaheuristic for the PI-hub allocation problem

D	N	#Trucks	BFGH	SA	Heuristic VS SA (%)	SA − CPU time (s)
4	60	26	1,987.05	1,878.16	5.48	90
	90	29	2,859.21	2,743.50	4.04	130
	133	41	4,256.28	4,079.54	4.15	185
6	60	29	1,966.97	1,818.66	7.53	70
	89	33	3,013.98	2,872.56	4.69	128
	137	41	4,693.44	4,544.19	3.17	180
10	60	25	2,123	1,960.68	7.64	91
	89	35	2,984.79	2,854.75	4.35	87
	129	42	4,419.80	4,206.82	4.81	103
15	60	27	1,992.69	1,868.15	6.24	63
	90	34	3,404.08	3,056.20	10.21	97
	128	47	4,426.15	4,256.01	3.84	200

7 Conclusion and Perspectives

The allocation problem in the rail-road hub in physical internet context is considered. This problem concerns the allocation of both containers to destination docks and docks to trucks. A simulated annealing metaheuristic based method is proposed to deal with the problem. The objective is to minimize the distance covered by containers to be moved from train to trucks (docks) according the target destination. The results are compared to an existing heuristic proposed in previously research.

Heuristic and metaheuristic are implemented, tested and compared using generated instances. The results obtained by SA metaheuristic show an improvement of the criteria about 5 % compared to BFGH heuristic.

Future works will be oriented to three issues. First, we are working to improve the metaheuristic by defining other neighbouring solutions. Second, more objectives will be also used which implies the use of other metaheuristics to solve the problem. Finally, perturbations and uncertainties will be defined and integrated to test approaches in real-world context.

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Human-in-the-Loop Cyber-Physical Production Systems Control (HiLCP$_2$sC): A Multi-objective Interactive Framework Proposal

Mehdi Gaham, Brahim Bouzouia and Noura Achour

Abstract Human-in-the-Loop Cyber-Physical Production Systems Control (HilCP$_2$sC) concept can be largely conceived as a natural evolution of distributed manufacturing control paradigms which exploits recent technological progresses in embedded systems, ICT and networking and communication infrastructure, and where Human-System interactive dimension of Cyber-Physical Systems (CPS) plays a significant role as an enabler for intelligent decisional framework bringing human into the cybernetic loop of the manufacturing control system. The reported research concerns an on-going effort toward the introduction and the development of this concept and presents, as a preliminary technical investigation, the deployment within this context of a parallel multi-objective NSGA2-based high-level scheduling framework capable both of exploiting computational and communicative capabilities of the manufacturing systems Cyber-Physical components, and integration of human decision maker preference within the control process. Different conceptual and technical issues, and some earliest results related to this investigation are presented in the paper.

Keywords Cyber-physical production systems · Human-in-the-loop CPS · Multi-objective optimization · Flexible job shop scheduling

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M. Gaham (✉) · B. Bouzouia
Equipe Systèmes Robotisés de Production, Centre de Développement
des Technologies Avancées, Baba Hassen, Algeria
e-mail: mgaham@cdta.dz

N. Achour
Laboratoire de Robotique Parallélisme Electro-énergétique, USTHB, EL ALIA,
Bab Ezzouar, Algeria

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1 Introduction

Recently, the convergence of emerging embedded computing, information technologies and distributed control architectures became a key enabler for future manufacturing enterprises [1]. At a large scale, this convergence leads to the development of the concept of Cyber-Physical Systems (CPS) that refers to a new generation of systems with integrated computational and physical capabilities, and where atomic physical entities embedding computational and communication abilities interact in order to produce a global intelligent behaviour featuring autonomy, self-control and self-optimization. Opening new areas of innovation, CPS are expected to be a decisive driving force for advances in different applicative domains including manufacturing control [2]. Accordingly, Cyber-Physical Production Systems (CPPS) conceptualized and developed this last years by both industrialists and researchers community are expected to be the core foundation for the next industrial revolution and next generation manufacturing systems [3] and has attracted an increasing number of industrial excellence initiatives emanating from major industrial and developed countries. Mainly, CPPS can be conceived as a natural evolution of distributed manufacturing control paradigms, such as Holonic-based [4], and Product-driven approaches [5], that exploit recent technological insights concerning embedded computing, networking and ICT technologies. The major particularity of CPPS emanates from their conceptual ability to promote human-machine and human-system interaction that is one of the key development issues in CPS. With the use of dedicated cooperative interfaces, the human is therefore considered as a part of the CPPS and hence can naturally supervise, collaborate and interact with the different decisional levels of the manufacturing control system or the distributed entities themselves.

The presently reported research concerns an on-going effort toward the development of a human-in-the-Loop Cyber-Physical infrastructure for manufacturing systems dynamic scheduling and control. It focuses at this stage of the project on one of the main components of the infrastructure, which is the adopted multi-objective online scheduling framework in the human-system interactive decision making process, used during steady state operations of the manufacturing system. An online parallel NSGA2 approach for scheduling flexible job shop problems is presented, as a preliminary technical investigation. Implemented using an agent-based technology, the proposed framework tackles two main conceptual issues: (i) using “a posteriori” multi-objective optimization framework, it introduces implicitly the human decider into the cyber-physical decisional loop, and (ii) owning to its agent-based parallel implementation it can be distributed over the cyber-physical manufacturing system components. This last issue is of particular concern when dealing with resources and time consuming online multi-objective optimization algorithms.

The rest of the paper is organized as follow: Sect. 2 outlines the introduced concept of Human-in-the-Loop Cyber-Physical Production Systems Control. Section 3 highlights the architectural and functional framework of the proposed research. The adopted multi-objective NSGA2 Flexible Job Shop scheduling method is presented in Sect. 4 and the experimented JADE-based parallel implementation scheme of the approach, as well as preliminary results are presented in Sect. 5. Finally Sect. 6 concludes the paper.

2 Human-in-the-Loop Cyber-Physical Production Systems Control

Cyber-physical systems (CPS) can be described as smart systems that encompass computational (i.e., hardware and software) and physical components, seamlessly integrated and closely interacting to sense the changing state of the real world [6]. Using CPS, the physical world is being linked seamlessly with the virtual world of information technology into an Internet of Things, Data and Services [7]. These systems will transform the way humans interact with—and control the physical world [8]. As well, by integrating perception, communication, learning, behaviour generation, reasoning into such systems a new generation of intelligent and autonomous systems may be developed [9].

In the manufacturing domain, CPS are expected to motivate a more integrated and intelligent vision of the enterprise [10]. CPPS comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently [7]. As in Holonic and Product-Driven approaches, CPPS also promotes the integration of manufactured product as a communicative and active cyber-physical component: the “Smart Product”.

Human-System interaction and human integration in the Cyber-Physical world is of main concern in CPS. As explained in [6]: “achieving effectively networked, cooperating, and human-interactive systems will be an integral factor in the adoption of CPS. In the future, networked, cooperating human-interactive systems will optimize the power of human operations through high levels of situation awareness and adaptability”. So, Human-System interaction is now one of the main focuses of different foundation works concerning Human-in-the-Loop robotic CPS [11] being investigated in an increasingly number of applicative areas. It is thus recognized that human-in-the-loop cyber-physical systems (HiLCPSs) comprise a challenging and promising class of applications with immense potential for impacting the daily lives of many people [11]. This potential of HiLCPSs is also identified in the manufacturing domain where Human-System Interaction for technologies learning and assistance plays a key role in the development of the factory of the future: the *smart factory* [6]. Besides, different researchers have addressed in the past the potential of integrating the human decider in the manufacturing planning and control decisional process. Investigating foundations of that concept, some of them [12] stated the importance of integrating the human operator’s intelligence into manufacturing management systems in order to enhance responsiveness. Besides, in the same reference it is clearly admitted that the integration of multi-agent architectures, advanced display concepts and multi-criteria and distributed decision support systems represents the right approach.

Motivated by the presently outlined research context, this paper deals with the concept of Human-in-the-Loop Cyber-Physical Production Systems Control (HiLP$_2$sC). In this type of system the human supervisor plays a significant role as an active part of the online management decisional process. The human is hence integrated into the manufacturing system's decisional cybernetic-loop and participates to the elaboration of the overall behaviour of the system using a transparent framework based on interactive multi-objective evolutionary scheduling approaches. Actually, the interactive dimension of CPS is of main significance for online manufacturing scheduling and control tasks. Using components-related real-time information, the human is expected to collaborate with the control system to make a situation aware scheduling decision. Also, this systemic collaborative capability of CPS is of particular interest for hybrid predictive-reactive multi-agent manufacturing control architectures where a high level predictive scheduling process is still in use beside the decentralized one, which is involved during highly disruptive situations. Besides, it copes effectively with complex manufacturing where a variety of simultaneous optimization criteria can be involved during online decision making process and where a multi-objective decision framework involving human decision maker expertise has to be deployed.

3 Human-in-the-Loop Cyber-Physical Production Systems Control Architecture

At decisional level, a multi-agent hybrid architecture is used in this work for the implementation of the Human-in-the-loop cyber-physical manufacturing control infrastructure. In [13] a rigorous classification and a state of the art review of hybrid manufacturing control architecture is given. Accordingly, the adopted architecture in this work is classified in the Class II-SHo group that designates Hybrid Static Homogeneous control architectures. Control architectures falling within this group are characterized by the hierarchical integration of a high-level centralized optimizer and low-level distributed, communicative and decisional entities that follow high-level order. In the case of disruptions, the entities are also capable of interaction with the high-level decisional optimizer to trigger a rescheduling process. Main architectural features of the proposed Cyber-Physical Infrastructure are depicted in Fig. 1.

The lower architectural level is composed of the cooperative Cyber-Physical manufacturing entities in charge of the dynamic behaviour of the CPPS. The higher level is responsible of the elaboration of an optimization-centric global scheduling decision that guides the lower level decision in stable manufacturing situations. Cyber-physical Human-System interaction is implemented at this decisional level by the use of an evolutionary multi-objective and interactive

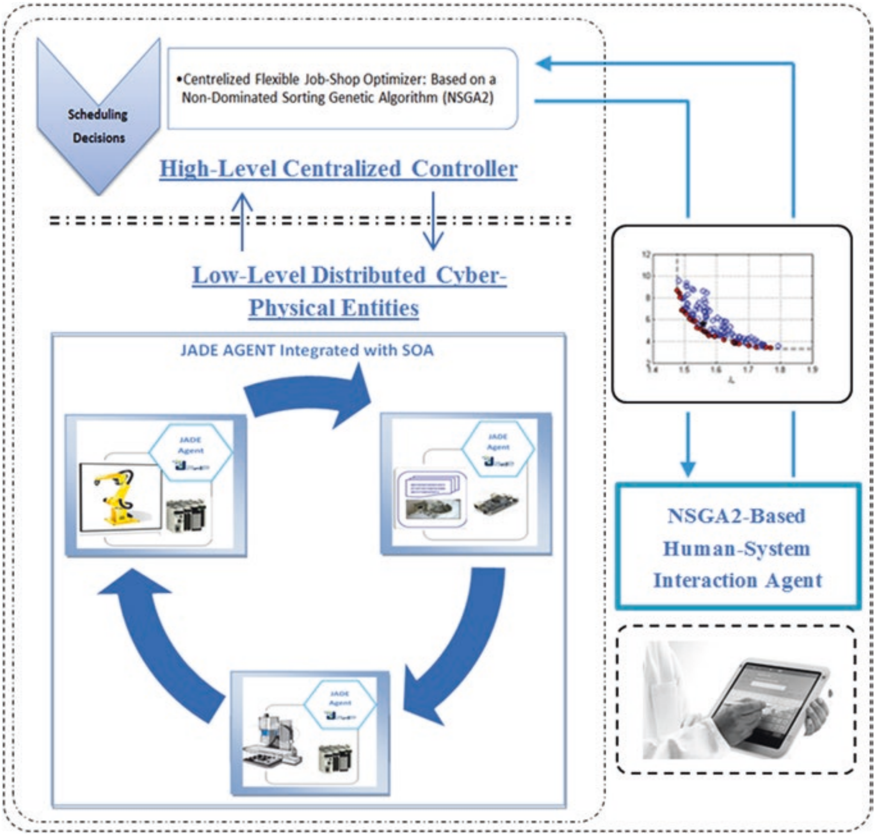

Fig. 1 Human-in-the-loop cyber-physical production system control architecture

scheduling framework that integrates the human's context-aware preferences in the optimization process. At this stage of the project, the interactive dimension of the CPPS is endeavoured by an a posteriori Flexible Job Shop NSGA2 scheduling scheme, where a representation of the set of Pareto optimal scheduling solutions is first generated and then the human is supposed to select the most preferred one among them according to its preferences.

In the following sections, issues related to the parallel implementation of the evolutionary multi-objective scheduling framework are presented.

4 Parallel NSGA2 Approche for the MO-FJSSP

Different approaches, for their great part articulated around population-based meta-heuristics have been proposed in the literature in order to tackle the multi-objective nature of the FJSSP (see for example [14, 15]). As a representative model in machine scheduling problem with a broad real world application's spectrum, the flexible job shop scheduling problem (FJSSP) is chosen in this study as a working model for the implementation of the higher decisional level. Indeed, the problem is commonly defined as an important extension of the classical job shop scheduling problem (JSSP) that allows operations to be executed by a machine chosen from a predefined set of available ones. The following criteria are considered in this study: $C_{\max}$, the completion time of all the jobs with C_i the completion time of job J_i, $W_{\max}$ the maximal workload of all machines in the system, with W_k the workload of machine M_k, and T_w the total workload of all machines in the system. Minimizing the total working time of all machines is of interest if minimization of machines utilization is sought.

The predominant declination of the Non-Dominated Sorting Genetic algorithm, known as NSGA2 [16] is adopted for this study as a multi-objective optimization framework. Inspired by the processing behaviour of the canonical Genetic Algorithm, the algorithm is manly based on the notion of Pareto dominance. Particularly, it promotes during the evolutionary process the non-dominated solutions in order to obtain a Pareto front as a result, and incorporates a crowding mechanism that preserves the diversity of solutions in the Pareto front. The crowding distance is based on a kind of evaluation of the closeness of solutions in the front to a considered one. Besides, the algorithm considers elitism by incorporating systematically the old population and the newly generated one (by using selection, crossover and mutation) in the mating pool.

The overall framework for one generation of the algorithm is depicted in Fig. 2. A combined population of the considered population at generation *t* and the

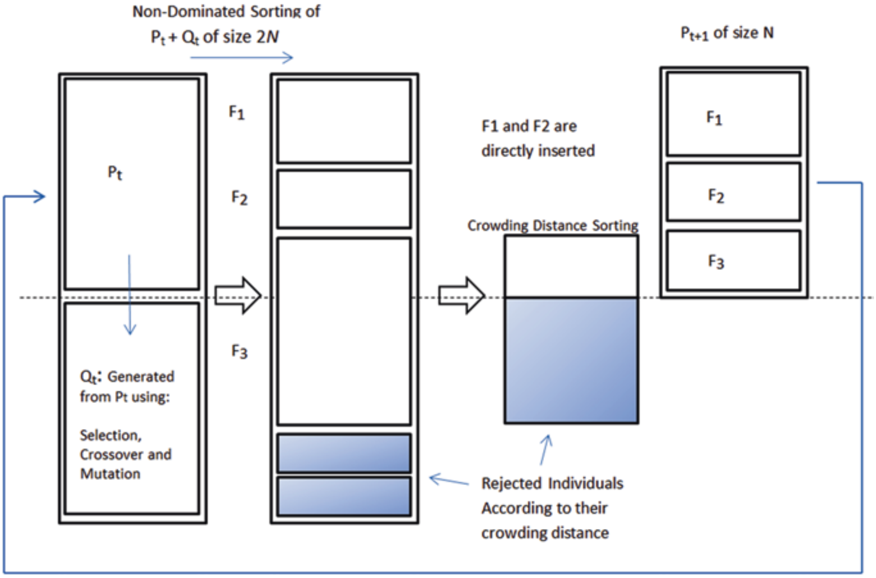

Fig. 2 NSGA2 framework

generated population using crowded tournament selection, crossover and mutation operators is non-dominated sorted. In crowded tournament selection that is a specific operator to NSGA2 algorithm, the winner individual of two same-rank solutions is the one that has the greater crowding distance value. Different Pareto front including the best one with totally non-dominated solutions are then identified. All best fronts witch have a summed number of individuals smaller than N (population size) are introduced in the new population. The remaining front, if it exists is sorted according to the crowding distance of the individuals and the best ones are used to fill the remaining empty positions in the new population. For an extended description of the NSGA2 algorithm and most important implementation issues, such as the fast non-dominated sorting procedure and the crowding distance calculation, the reader is reported to [16]. Genetic algorithm coding and decoding schemes and the adopted recombination operators have been in this work mostly inspired by the different declinations of evolutionary approaches for the JSSP found in literature.

Different sophisticated and effective paradigms for parallel implementation of GA (PGA) have been proposed in literature. In this paper we adopt the Multi-Population Island model. The Island or coarse-grain model is a Multi-population and multi-processor approach in which each population has its own independent evolution process. The cooperation between islands is achieved by the Migration Operator. According to some predefined migration strategy and topology, individuals migrate from one island to another to share information and enhance explorative power of the optimization process.

As illustrated in Fig. 4, in this research work we use an island Multi-Population NSGA2 model with a fixed Ring topology (unidirectional). Beside, an asynchronous migration policy with fixed migration rate and frequency is used. Explicitly, at each predefined number of generations (migration frequency), each island sends a certain number of individuals to its neighbour island (Migration Rate). At the same generations count, it integrates received individual from the second neighbour island in its current population using a replacement policy that considers the fitness of the individual.

5 Implementation Issues and Preliminary Results

As previously mentioned, Human/System Interaction is endeavoured by a Flexible Job Shop NSGA2 scheduling scheme, where a representation of the set of Pareto optimal scheduling solutions is first generated and then the human is supposed to select the preferred one.

As depicted in Fig. 3, the interaction between the Human Decider (HD) and the parallel multi-objective scheduling algorithm uses an “a posteriori” protocol: after have been triggered by one of the system’s agents, the HD is asked for a rescheduling decision by the Interaction Agent (IA)—see lines 1, 2 in Fig. 3.

If a rescheduling decision is taken by the HD, the IA initializes the rescheduling problem and asks the registered agent (embedded in computing

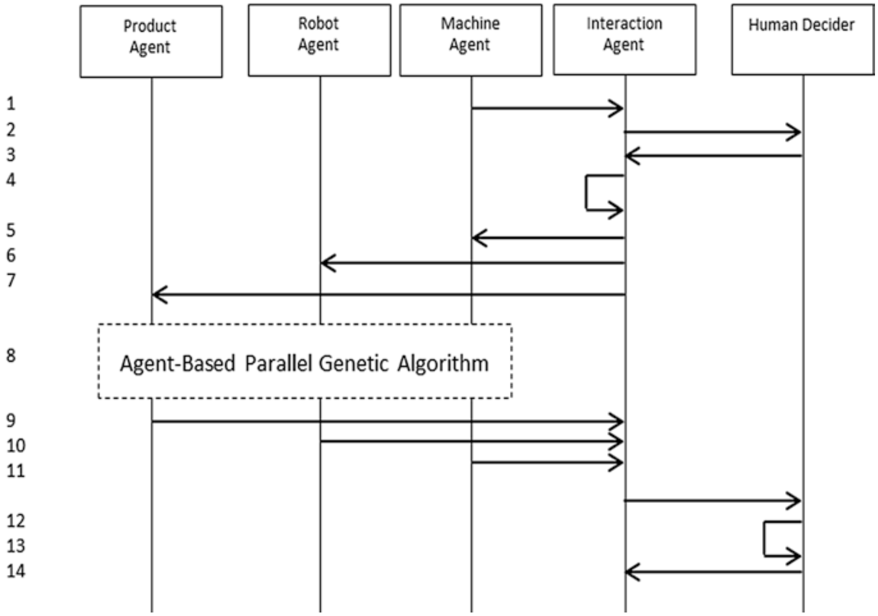

Fig. 3 Human/System interaction protocol

devices associated to the manufacturing Cyber-Physical System components) to run the parallel genetic algorithm (see lines 3–8 in Fig. 3). After having been generated, the Pareto optimal set is presented to the HD by the IA and the appropriate solution is selected by the HD to be used by the system (lines 9–14 in Fig. 3).

Also and as highlighted in Fig. 4, the parallel Agent-Based implementation of the NSGA2 scheme uses the embedded computing capability of the Cyber-Physical manufacturing System components, and is deployed considering corresponding computing devices (for example a tablet for an Intelligent Product). Besides, because it copes effectively with such implementation issues, the parallel optimization approach and the overall framework use the Java Agent Development framework JADE. This technical choice is principally motivated by the capabilities of JADE Agents to run under mobile computing and communicative devices (for example embedded in the intelligent product such as in [17]) and its transparent integration with services architectures (see [18]).

At this stage of the on-going implementation the agent-based multi-objective genetic algorithm has been implemented and tested on common FJSSP instances from literature. As primary results, the Pareto Front of an example FJSSP instance consisting of 10 jobs and 6 machines and considering the three aforementioned FJSSP objectives is presented in Fig. 5. The obtained results are clearly satisfactory at this stage of the research.

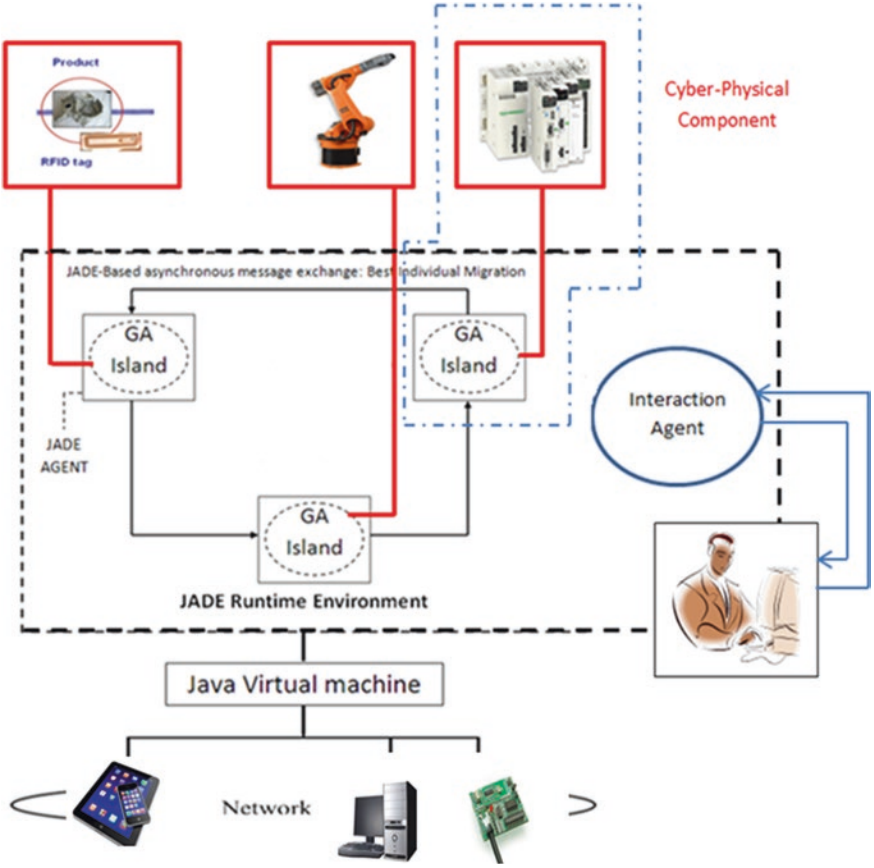

Fig. 4 Implementation framework

6 Conclusion

The present paper introduced the research concerning on-going development of a Human-centred Cyber-Physical infrastructure for dynamic scheduling and control of manufacturing systems. Thus, the concept of Human-in-the-Loop Cyber-Physical Production Systems Control (HiLCP$_2$sC) has been introduced and implemented according to the current requirements of manufacturing. The principal features of the proposed control architecture were also succinctly presented. As a core development issue, the Interactional multi-objective NSGA2 adopted framework as well as its application to the flexible job shop scheduling problem were described in more details and exemplified through preliminary experimental results.

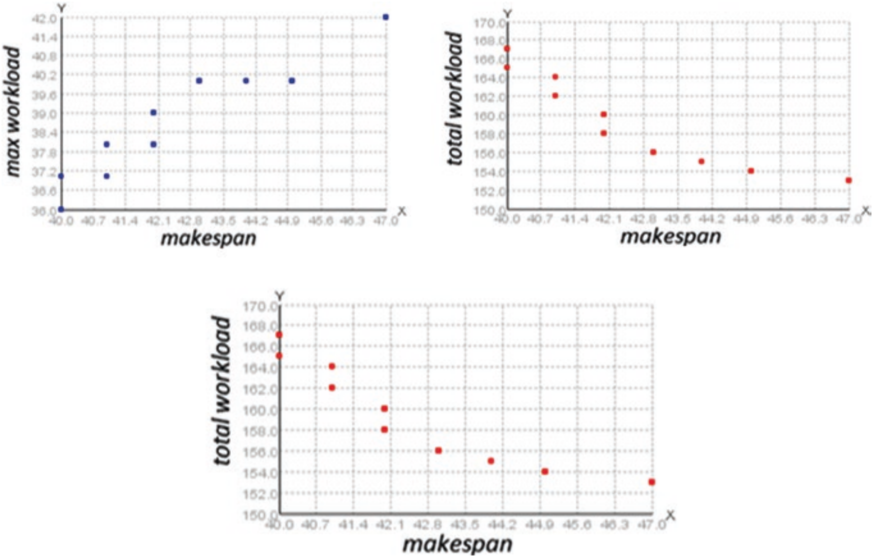

Fig. 5 Experimental results

Future directions of the research will concern two major issues: (i) the investigation of a more effective interaction framework based on interactive multi-objective approaches, and (ii) the experimental investigation of the concept with the integration of real world technological factors (embedded computing and SOA).

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