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A database-centric approach for the modeling, simulation and control of cyber-physical systems in the factory of the future.

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The path towards Industrie 4.0, requires that factory automation problems cope with the cyber-physical system complexity and its challenges. Some practical experiences and literature in the field testify that the role of the database management systems is becoming central for control and automation technology in the new industrial scenario. This article proposes database-centric technology and architectures that seamlessly integrate networking, artificial intelligence and real-time control issues into a unified model of computing. The proposed methodology is also viable for the development of simulation and rapid prototyping tools for smart and advanced industrial automation.

Keywords: Computational methods, Database management systems, Distributed computer control systems, Embedded systems, Industry automation, Intelligent manufacturing systems, Simulators.

1. INTRODUCTION

The factory of the future is in the objectives of the *Industrie 4.0* strategy. Cyber-physical systems (CPSs) are the new research framework that makes the complexity of the Industrie 4.0 goals treatable and where physical and software components are deeply intertwined to interacting each other in a myriad of ways that change with context (Lee 2015). The efficiency measurements and assessment of industrial production processes in the future scenario have to take into account the increasing role of information flow across processes from the enterprise system level down to the shop-floor. Information is the main vehicle that allows humans to be in control of sustainability and productivity and allows the introduction of artificial intelligence as a decision support tool. The appearance of unforeseen behaviours is a typical phenomenon of complexity: new features and prospects might emerge from the deliberate application of data mining techniques coupled with artificial reasoning and inference on already well known and established data. Indeed new opportunities would originate from the full exploitation of information acquired, stored and communicated in industrial processes. Most of it unfortunately, due to the high volume of data, is usually doomed to be neglected as noise rather than useful added-value information. Though expensive smart metering methods are common, on current manufacturing plants, they should deserve a deeper exploitation.

This paper proposes an "information-conservative" approach suggesting a key enabling technology and a methodology for modeling, control, simulation, planning, optimization and scheduling of industrial processes, through dynamical assessment of some common key performance indicators (KPIs). The key approach is the pervasive use of relational database systems that actively support transmission, storage and elaboration of information across the 5 levels defined in the ISA-95 standard – from sensing and actuation to the management of a network of enterprises. The traditional 5 ISA-95 levels seem designated to be blurred and surpassed soon by the new smart factory technologies and concepts. It is expected to move from the existing hierarchical control structures, based on the ISA-95 automation pyramid, towards more decentralized and reconfigurable structures based on the CPS principles (Leitao 2015). Indeed cyber-physical production systems (CPPSs) will show cyber capabilities within every physical component, as distributed computing along with distributed intelligence, and 'self-*' methods, namely: self-adaptation and self-configuration, along with self-diagnosis, self-organization and self-reconfiguration dynamics, as required through the *Industrie 4.0* strategy.

The introduction of an active distributed database mechanism at the shop-floor, through the best embedded database technologies today available, renders the data mining and the optimization of processes viable for the CPS challenge. By the use of the quality of a declarative language, as the database languages in the relational model, most of the techniques for planning and optimization (Jeon 2016) can be enabled dynamically. Decision support systems based on time-aware relational model inference can lead towards results potentially unforeseen at the beginning of the information gathering (Yang 2016, Nickel 2016, Date 2014). The full relational model will require more scientific effort in the future but a restricted database-centric technology based on the established SQL database language standard can create a first technological step towards the challenges made up by the smart manufacturing scenario.

We propose guidelines and technology hints that can be effectively used in KPI-based control for the energy efficiency of industrial processes within the sustainable factory of the future research framework (Stiel 2016).

In section 2 we introduce related work on the basic ideas of the database-centric technology. In section 3 a problem

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description along with a technology description and its unifying role for industry is provided. In section 4 a simulation and modelling methodology is introduced. In section 5 the results expected from the methodology are discussed. Section 6 is for conclusions.

2. PERVASIVE DATABASE TECHNOLOGY AND RELATED WORK

Information is gold, and nothing of it should be lost. On the top of it we can decide different views with their different resolutions and granularity. As the level of aggregation of information increases, the influence of changing structural effects and other factors are lost as some emergence over the data might remain statically frozen by aggregation itself. Going down towards the lower and more detailed levels increases the understanding of the multitude of factors that affect energy efficiency, to make smart production decisions. However, as we go to details the quantity of data and sensing becomes complex, and this complexity is unavoidable in the cyber-physical systems scenario. We have to cope with that complexity in a clever and lean way. The appropriate level of detail for the construction of energy efficiency indicators can be controlled through the application of a methodology based on pervasive database management systems (DBMSs).

Industrial production processes are complex and the heterogeneity of the components and protocols across the factory floor, and its organizational and geographical boundaries, create strong demands for system integration and interoperability (He 2014). Valuable unifying efforts towards standards, like the OPC UA (Mahnke 2009), have been well established. In any case, this computing model might not be completely able to scale down and keep up with the incoming CPS storm, mainly because those issues were not present at the time of its design. While in OPC UA the database is used mainly for historical data storage, in our proposed approach, each component or agent in the process is provided with active database capabilities that tracks data and events to trigger control on the plant. Information is made constantly available for its use at the highest strategic levels, where decisions cope with the long-term issues. Decisions made at the strategic level can influence the procedures implemented at lower levels through dynamical programming based on planning and reasoning with context awareness. By using distributed computing techniques and tools, we can keep the costs of complex solutions low and viable. The technique of adding a database everywhere does not necessarily require a change in the lower level technology or acquisition system. It can be applied on top of existing facilities. Distributed databases for CPSs imply networking as we have to include the Internet of things (IoT) inside. In (Jia 2013) it is shown how the IoT promise of integrating the digital world of the Internet with the physical world needs to be implemented through a systematic approach for integrating the sensors, actuators, where data is the central entity for the realization of context-aware services. In (Rajhans 2014) it is shown how abstraction of models is necessary in the current complexity of CPSs. For this kind of abstract modelling we put forth the expressiveness of the relational model, or where not fully available, at least the ordinary relational database technology with the plethora of extensions provided from SQL database systems vendors. Nowadays, some industrial producers like Inductive Automation™ already use this kind of database-centric technique (white paper 2012). They use a SQL database as the centre of every software and business logic of their industrial automation application. In (De Morais 2014) the author shows how data processing can be integrated and performed within the DBMS. Both the formerly cited solutions are going in the right direction lest the necessary scalability foreseen in cyber-physical systems is still lacking. In CPSs the database must scale down to use a minimum of resources (potentially below 1MB of memory). Therefore, the SQL DBMS implementation needed, must fit the requirements of special purpose embedded solutions. A viable DBMS implementation could be represented from the very portable and mature SQLite which is released in public domain and is apt and open to innovation and research. Nevertheless, a major drawback in the SQL approach is the SQL itself. Notably, SQL falls short when it has to cooperate with artificial intelligence. Although SQL database language is a declarative and 4th generation programming language, it doesn't supply the expressiveness needed, for example, in first order logic inference problems. The real model that should be adopted and implemented soon is the relational model in the original Codd's sense (Codd 1990) reviewed by some followers (Darwen 2012). The relational model in general can act as a higher-order logic representation language, so fit to cope with all problems and inherent limitations of SQL (e.g. SQL has not a standard query for asking a list of the database tables, or treat a table itself as a variable. This is usually overcome by producers with proprietary extensions). Unfortunately, no lightweight implementation of the relational model is already available. Until the availability of research efforts in the relational model implementation sense, we are left with SQL and its shortcomings. Besides, SQL based automation still can represent a great step forward in the paradigm for industrial process control right now. Means and techniques to adapt SQL to artificial intelligence (AI) have been already developed (Schuldt 2008, AlAmri 2012, Bhatia 2013). The use of SQL as a base technology for AI and automation is promising and is the straightest path towards managing the complexity of CPSs challenges.

3. FACTORY AND PROCESS AUTOMATION PROBLEM

A DBMS-centric approach for complex process automation was already looked into through the federation of MySQL and PosgresSQL technologies in 2008 in the developments of a European FP7 research project (CAFE 2008). MySQL was used for embedded units as a moderately lightweight DBMS solution for embedded Remote Terminal Unit (RTU) boards while PostgreSQL was used as the remote global data centre. The major concept put forth there was the unifying role of the DBMS to host heterogeneous technologies for acquisition, actuation and data processing. With suitable and simple adapters, any sensor and actuator, along with special purpose computing units and machines, were connected in a whole unified DBMS informational centre. In Figure 1 we show the unifying role of DBMS-centric technology in an architecture