IMC-AESOP Outcomes: Paving the way to Collaborative Manufacturing Systems

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***Abstract*—Industrial automation systems have been established in various domain over the past decades exploiting standards, dedicated to network protocols, resource models, interfaces, programming languages etc. While systems increasingly get networked, the potential of their interactions and collaboration, especially in large-scale and complex settings, may unveil new business opportunities. A series of challenges have been systematically tackled the last years and demonstrated the feasibility of key parts. Among them, the IMC-AESOP has paved the way from web-service enabled systems to cloud-based industrial cyber-physical systems, and demonstrated with real industrial use cases various aspects with respect to next generation supervision control and data acquisition (SCADA) that may empower collaborative industrial systems. In this paper, a selected set of innovative results achieved within the IMC-AESOP project are summarized - migration strategies to the application of service based communication, system-wide introduction of Complex Event Processing capabilities, integration concepts between different generations of technologies and provision of cloud capabilities across different levels of production systems as well as experimentation in real industrial applications.**

Keywords*— *collaborative manufacturing systems; cloud-based automation systems; service oriented architecture; cyber-physical systems

I. INTRODUCTION

In the last decade significant changes in the industrial automation domain have taken place, such as the rapidly increasing penetration of Internet technologies and concepts, which increased openness, interconnection, information-driven integration and cross-layer interaction [1]. In a fast changing world, agility is a competitive advantage for modern enterprises. The latter means that decisions need to be made based on real-time data and in parallel be enforced not only at local industrial processes but factory-wide as well as at several partners that interact with them. This is challenging, especially when the whole business network ecosystem is considered, which itself is a System of Systems (SoS) [9] [10]. Bringing it together with collaborative automation concepts may increase the competitive advantage and provide significant benefits; however, doing so assumes effective tackling of several technical and architectural challenges.

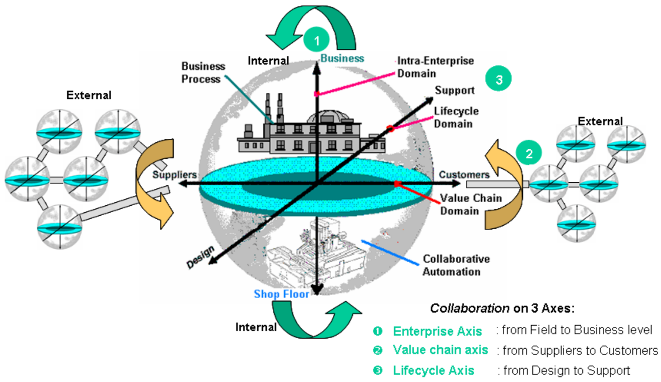

Figure 1. Collaborative Manufacturing Model Paradigm - a System of Collaborative Systems [3] [4].

Today, implemented "Collaborative" Industrial Systems of Systems should be distinguished from large but monolithic systems by the independence of their inter-related components. Following the Collaborative Manufacturing Model (CMM) paradigm [2] [3] (as depicted in Figure 1), those systems are on the one side generally distributed along the supply chain and the enterprises axes, and on the other side they are from evolutionary nature, showing emergent behaviours along the life-cycle axis. They present a geographic extent that generates strong limitations to mainly interact by data and information exchange and only sometimes also physically exchange of material and energy. Related to the Enterprise axis, factories are structured, from the administrative as well as from technical or IT infrastructure point of view, in a hierarchical manner. Complexity becomes increasingly visible as systems are often composed as sets of numerous other systems, usually including separate systems for plant operation, maintenance, engineering and business.

These systems are usually multi-disciplinary and heterogeneous with limited interoperability.

The Factory of the Future (FoF) will rely on a large ecosystem of systems where collaboration at large scale will take place. The collaborative vision is affected by disruptive technologies and concepts, including Service Oriented Architectures (SOA), Cloud Computing and Cyber-Physical Systems (CPS) [11]. The result will be a highly dynamic flat information-driven infrastructure that will empower the rapid development of better and more efficient next generation industrial applications while in parallel satisfying the agility required by modern enterprises.

Designing and operating the factory of the future means dealing with several challenges such as structural, operational and managerial independence of the shop floor and enterprise constituent systems, interoperability, plug and play, self- adaptation, reliability, energy-awareness, high-level cross-layer integration and cooperation, event propagation and management, etc. (see Chapters 1 and 11 of [14]). As such the different systems composing the whole enterprise will be part of a distributed ecosystem, where components, hardware and software, can dynamically be discovered, added or removed, and dynamically exchange information and collaborate. This cross-layer, intra-enterprise collaborative infrastructure will be driven by business needs exposed and managed as individual and/or composed services by the system's components [15].

Significant effort has been invested towards laying down the fundamentals of structuring complex production systems, defining models and exchange formats of information representing different aspects of equipment used or to define suitable protocols for horizontal or vertical communication. There are numerous standards addressing that area on global or specific level. The most commonly used in practice are the definitions set up within the ISA 95 (www.isa-95.com) and IEC 62264 standard [5].

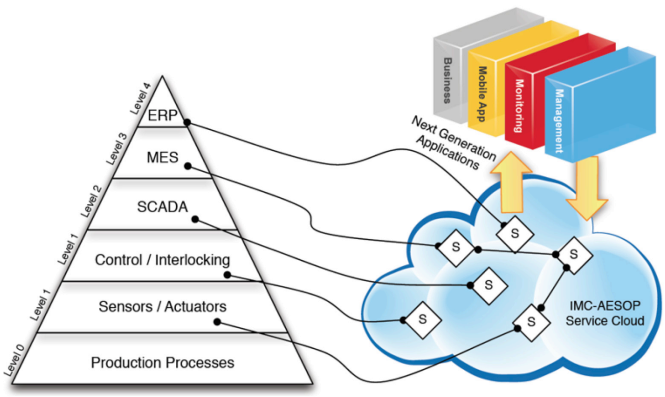

Figure 2. Future industrial system view of cloud-based composition of cyber-physical services

Service oriented architectures are seen as a promising concept for overcoming the situation of having diverse inhomogeneous interfaces [1], and cutting edge research projects such as SOCRADES (www.socrades.eu) and IMC-AESOP (www.imc-aesop.eu) [14] have shed new light to the way service oriented architectures can be used within automation and integration into production control, automation and management applications, as extensively described in Chapter 2 of [14]. SOCRADES was dedicated to investigate the SOA use in manufacturing applications with focus to integration and communication characteristics to be supported by production management and control components distributed across several layers. The IMC-AESOP project has taken a further step and proposed a new information-driven interaction among the different layers and systems (as shown in Figure 2), which is cloud-based [7]. With the empowerment offered by modern service-oriented architectures, in theory the functionalities of each system or even device [8] [1] can be offered as one or more services of varying complexity, which may be hosted in the cloud and composed by other (potentially cross-layer) services.

The fusion of SOA, Cloud Computing, and Cyber-Physical System in an information-driven infrastructure (as shown in Figure 2) marks a paradigm change in interactions among the different systems, applications and users. Although the traditional hierarchical view coexists, there is now an alternative/complementary flat information-based architecture available that depends on a big variety of services, exposed by the cyber-physical systems as well as their orchestration, composition, and choreography.

II. Building Blocks for Collaborative Automation Systems

In the effort to realise the collaborative automation paradigm, it is needed to effectively develop tools and methods, to achieve flexible, reconfigurable, scalable, interoperable network- enabled collaboration between decentralized and distributed Cyber-Physical Systems. A first step towards this infrastructure is to create a service-oriented ecosystem. That is, networked systems that are composed by smart embedded devices that are Web service compliant, interacting with both physical and organisational environment, able to expose, consume and some- times process (compose, orchestrate) services, pursuing well-defined system goals. The next step is to take advantage of modern capabilities in software and hardware, such as the Cloud and the benefits it offers.

Within IMC-AESOP project these advances were demonstrated by applying SOA and Cloud concepts to next generation of SCADA/DCS systems. While identifying and defining affected SCADA/DCS services, fundamentals for encapsulating typical characteristics of such systems are laid down. Combining this approach with concepts coming from cloud computing [7], a promising potential is witnessed in using these services at the application layer executed on real or virtualized resources of a next generation SCADA.

Such an ambitious approach could only be made possible through a comprehensive approach, based on SOA and coupled with the latest suitable technologies. Guaranteeing success means defining the elements for seamless integration of traditional (legacy) systems, as they are installed today, into SOA and cloud solutions. All this has impressively been demonstrated within four industrial pilot applications as illustrated in Figure 5.

A. *Architectural achievements*

A general overview of the service-oriented architecture developed by the IMC-AESOP consortium is explained in Chapter 3 of [14] and depicted at high level in FMC notation (www.fmc-modeling.org) in Figure 3. On the left side are shown the users who interact with the services (depicted in the middle). The data depicted on the far right side can be accessed with the necessary credentials. Although the majority of these services are considered for running on the "Cloud" some of these may be distributed and run in more lightweight versions on devices or other systems. As long as the SOA-based interaction is in place, they are considered as part of the general architecture view.

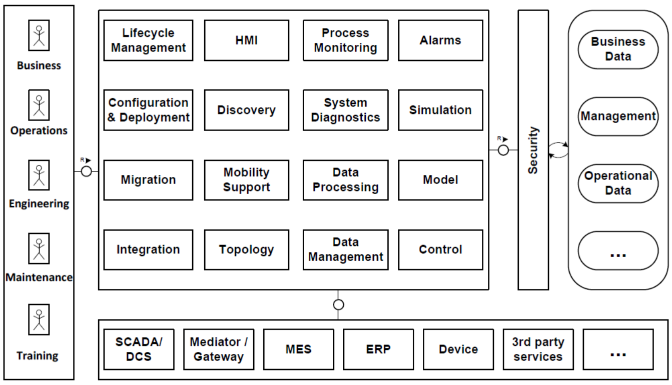

Figure 3. IMC-AESOP Architecture Overview

It is possible to distinguish several service groups, namely: Alarms, Configuration and Deployment, Control, Data Management, Data Processing, Discovery, HMI, Integration, Lifecycle Management, Migration, Mobility Support, Model, Process Monitoring, Security, Simulation, System Diagnostic, Topology. These groups indicate high-level constellations of more fine-grained services. All of the services are considered essential for next generation Cloud-based collaborative automation systems and they are defined based on a first prioritisation according to what the scientists and industrialists (partners of the IMC-AESOP consortium) considered necessary for future systems.

B. *Technology achievements*

To support establishment of this architecture, several key technologies have been identified and intensively assessed in the Chapter 4 of [14]. Among others, the technology associated to the Device-Profile-for-Web-Services (DPWS) [6], coming from the IT world, is one of the most applicable set of traditional Web services protocols, to be used at the device level. Combined with the Efficient XML Interchange (EXI), DPWS provides capabilities that can be used to cover some real-time requirements. OPC Unified Architecture (OPC-UA) [12], coming from the industrial world, is also a set of Web services protocols, and providing a data model enlarging the semantic capabilities of the solution. The Constrained Application Protocol (CoAP) can be used for wireless sensor networks. It can also be combined with EXI. This is still work in progress with major impact in the future once the technology matures. The Service Bus, the Mediator and the Complex Event Processing (CEP) are technologies providing the large scale and migration capabilities, combining and processing information coming through DPWS, OPC-UA or legacy protocols, in order to manage large-scale event-based systems. The initial investigations point out the potential of some of these technologies:

- The Embedded Service Framework (ESF), which is a redesigned, rewritten and extended version of the DPWS core stack (available at www.forge.SOA4d.org) was developed, assessed and demonstrated.
- As OPC-UA and DPWS have a large set of similarities, it is possible to build a common stack compliant with both standards where the two technologies can benefit from each other. A component implementing the convergence between OPC-UA and DPWS for embedded devices has been prototyped.
- Web service based technologies investigated so far at device level (DPWS, OPCUA, etc.) rely mainly on point-to-point communication models, which do not favour the system scalability. The "Service Bus" approach aims at decoupling service consumers from service producers in the industrial process control system. Large scale distributed systems can benefit from a Service Bus type middleware architecture as the bus acts as a broker between the numerous service consumers/providers, avoiding a potentially huge number of point to point connections.
- Complex Event Processing (CEP) relies on a set of tools and techniques for analysing and handling events with very low latency. The feature set for CEP spans from event extraction, sampling, filtering correlation and aggregation to event enrichment, content based routing, event compositions (and not only limited to these).

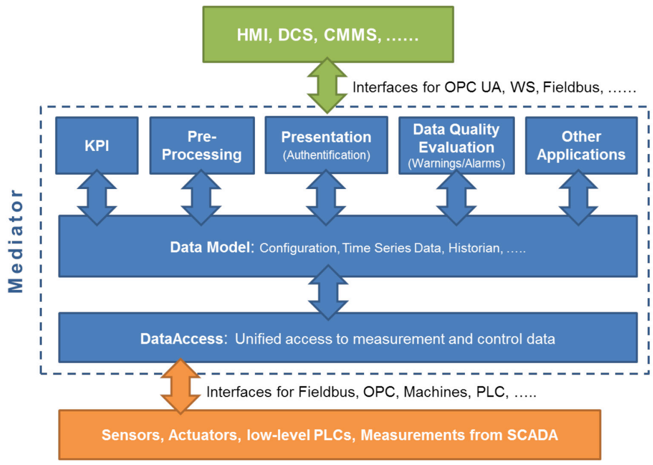

Figure 4. Overview of the Mediator concept

- The mediator (as illustrated in Figure 4) provides a runtime system for monitoring and control of process facilities by integrating both, legacy as well as SOA-based technologies. The core part of the Mediator consists of a data model that describes the logical view of the monitored facilities and also contains all relevant information for acquiring data including communication. For the integration of different communication protocols and information models of various devices and other data sources, an abstract data access layer has been introduced. By providing adapters, any required protocol can be integrated.

C. Bridging barriers between generations of industrial networks

The novelty of migrating from a traditional hierarchical ISA 95- based legacy process control system into a SOA-compliant ISA-95-based process control system has been proposed in a structured way by gradually upgrading highly integrated and vendor-locked standards into a more open structure while maintaining the functionality. More specifically, the migration concept defined [14], developed and prototyped in the project is not modifying the structural hierarchy of an ISA-95-based process control system but allowing it to functionally behave as a highly distributed flat architecture. This architecture is based on services located on physical components and/or on the cyber-space represented by an automation service-cloud. A procedure for migrating the functionality of a DCS/SCADA (ISA 95 Enterprise Architecture, Level 1 and Level 2) into a cloud SOA based implementation was proposed, developed and a prototype implemented at industrial level, which comprises four distinct steps as shown in Table 1, and makes use of mediator and service bus technologies.

Table 1. Functional Aspects mapped into Migration Steps of the IMC-AESOP Migration Approach [14]

Functional Aspect	**Step 1**	**Step 2**	**Step 3**	**Step 4**
Inter-protocol communication	X	O		
User management and security	X	X	O	
Operator manual override	(X)		O	
Operator configuration	(X)		O	
System Aggregation	(X)		(X)	(X)
Data acquisition, display and storage			O	X
Alarms and warnings			O	X
Local control loop	X			O
Emergency stop	(X)			O
Supervisory control		(X)		O
Distributed Control				O

Legend:
X: (partially) migrated, (X): can be migrated, O: mandatory migration

These four migration steps are designed to maintain the feeling of conformity between HMI and control execution and to ensure that the target system exhibits full transparency and supports open standards. The migration procedure is further analysed through a breakdown of the functionality of a SCADA/DCS and how the functionality can be migrated to SOA. Basically, considering the layout of a server/client-based SCADA/DCS a stepwise migration through the four major steps has been developed. The four major steps may contain sub-steps and may be spread out over a long period of time but each major step should be completed before the following step is initiated. Details are provided in Chapter 5 of [14].

D. Assessment of concepts

IMC-AESOP demonstrated the application feasibility of the achievements in various pilots that can be mapped on four real-world industrial use cases provided by end-user stakeholders as shown in Figure 5. More specifically:

- UC #1: The *plant lubrication* use case addressed a number of key points for the project, such as enabling SOA on low level devices, SOA in closed-loop control, integration into an traditional plant environment and migration from a scan based PLC to an event based SOA system. The lubrication system at the LKAB (www.lkabminerals.com) pelletizing plant KK4 in Kiruna, Sweden, is distributed to a number of independent black-box systems with limited data exchange between the lubrication systems and the larger distributed control system (DCS). In this use case one of these black-box systems has been migrated from the current implementation using a PLC to a SOA based system. The goal of the Use Case was to increase interoperability and information exchange by using SOA, while maintaining the required performance and reliability of operation on levels 1 and 2 of the Plant Lubrication System Architecture.

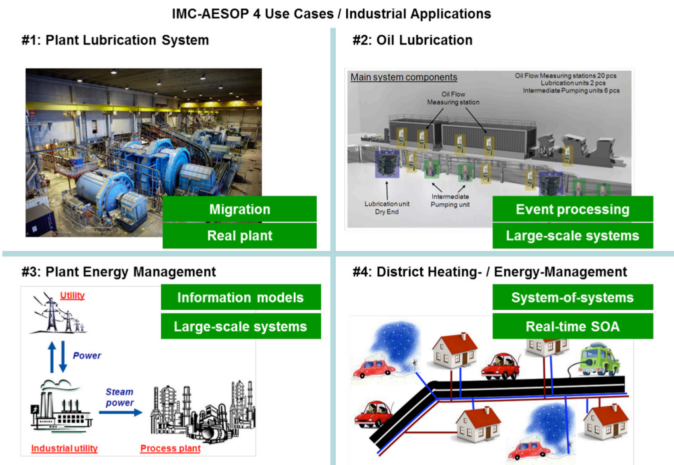

Figure 5. Overview of Industrial Applications implemented in the IMC-AESOP project use-cases

- UC #2: The *oil lubrication* use case addressed the manner in which lubrication systems in paper machines are monitored. Given that paper machines require the active lubrication of hundreds of different points, each of these points requires the existence of its own flow meter, and therefore its monitoring. In legacy systems, flow meters are monitored either manually by the process operators, or by elaborating monitoring systems that depend on traditional fieldbuses, or only allow for a single entity (monitoring room/computer) to show the captured information. This monitoring method, while in use, implies that the monitored information has to be either centralized or is completely unavailable. Additionally, the generated alarms are localized and grouped by stations, which generally makes identifying problems slow. This use case uses event based service oriented architecture, which is flexible, adaptable and agile. Services run both, on local hardware and remotely on a cloud service. The system architecture is based on distributed devices. The system can accommodate large amounts of devices and is easily scalable. Distributed devices supporting DPWS generate events that are processed with a complex event processor running in the cloud. Low level data is processed in order to support high level. Complex events from the CEP are sent to new generation SCADA system with open architecture and open protocols.

- UC #3: The main objective of the *plant energy management* use case was to highlight advantages of service orientation, event-driven processing and semantics for easier configuration, dynamic synchronization and maintenance of complicated multi-layer solutions, which are deployed nowadays in the continuous process plants. From the application perspective, this demonstrator is a combination of energy management and alarm management scenarios. This use case has not being deployed in a physical plant but in a simulated environment. Therefore two dynamic simulation models were used to simulate operating environment of the utility and process plants. The functionality is then centred around three main innovative parts:
    - energy management enhanced through cross-layer consistency management;
    - alarm management driven by Complex Event Processing;
    - scheduling of optimal charging of electric vehicles.
- UC #4: Within the *district heating-/ energy management* use case, the IMC-AESOP architecture was presented in the context of smart homes. A detached house connected to a citywide district heating network has been equipped with a Wireless Sensor Network (WSN), which is able to monitor and control the heat-balance of the house. In addition to heat control, the WSN can also monitor and react to a car approaching the garage. The system consists of several service-compliant embedded devices that are integrated with measurement sensors and actuators to perform surveillance and control of the heating system and surrounding systems [13].

III. Achievements and Future Directions

A. Summary of the IMC-AESOP Achievements

The major outcomes of the IMC-AESOP project, laying down essential fundamentals for building future CMS can be summarized as follows:

- Optimization of the operation of the plant provided by new monitoring indexes and control functions exposed and/or applied as Web Services (using discovery mechanism, event filtering, service composition and/or aggregation capabilities offered by the SOA and Web Services concepts).
- Process control and monitoring functions are now distributed. Plug & Play is being provided by discovery mechanisms, which are extended to work for large-scale distributed systems.
- Event-based mechanism can be used for process control and if sufficient performance for use in the lowest levels of control loops can be achieved.
- It is possible to build many different SCADA and DCS functions by combining the current centralized with the new SOA-based systems.
- The transition path considers the requirement that the new SOA-based process control system has to be an adequate legacy system in the next 5-10 years.
- The technical innovative results of IMC-AESOP such as real-time SOA and large-scale event-driven architecture are considered for standardization (e.g., www.oasis-open.org/standards).

The SOA-based approach proposed by IMC-AESOP can, on one hand, simplify the integration of monitoring and control systems on application layer; on the other hand, the networking technologies that are already known to control engineers could also simplify the inclusion of or migration from existing solutions and the integration of the next generation SCADA and DCS systems at network layer. Moreover, engineering methods and tools were investigated and highlights on the domain's future were assessed. The initial achievements paint a positive view for sophisticated collaborative systems, which will need to be further investigated in large-scale experiments.

B. Towards collaborative systems of systems

The fusion of Cyber-Physical Systems, SOA and the Cloud constitutes a significant step towards Collaborative Manufacturing Systems and their integration in cross-domain applications, i.e., Collaborative Systems of Systems [9]. The IMC-AESOP project demonstrated that the appropriate infrastructure will have to be in place and that web services offered/consumed by devices and systems, as well auxiliary services to enable their interaction play a pivotal role. By utilizing the new infrastructure, capabilities potentially not available at resource constraint devices can now be fully utilized taking advantage of Cloud characteristics such as virtualisation, scalability, multi-tenancy, performance, lifecycle management etc.

The Collaborative Manufacturing Systems should also be seen as integral part of other domains such as that of a smart city. Future smart cities will integrate multiple such systems in a harmonized way in order to enable new innovative services for their citizens. Hence, factories will be situated within cities, smart buildings and smart houses will take full advantage of the energy available in the grid, and all forms of energy by-products will not be wasted but fully integrated [16] e.g. for heating houses, public buildings etc.

This vision is depicted in Figure 6, which shows a system of systems from the energy viewpoint.

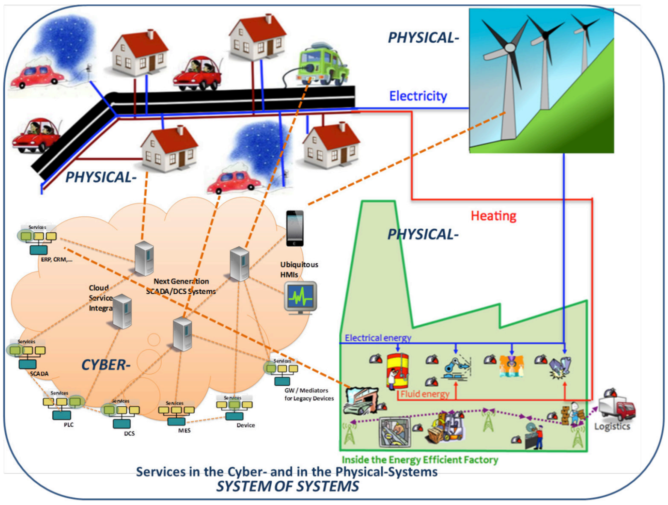

Figure 6. An IMC-AESOP System of Systems view empowered by Cloud-Based-CPS for the energy domain [14]

IV. CONCLUSION

Production systems, transportation systems, electrical generation and distribution, logistic systems, etc. are currently moving towards an heterogeneous infrastructure, a system of connectable and more and more interoperable systems that increasingly depends on monitoring of the real world, timely evaluation of data acquired and timely applicability of data to support management, control and automation of that real heterogeneous digitalized cyber-physical world. This implies that several new research, development and implementation challenges arise, such as: (i) Future factories are expected to be complex System of Systems (SoS) that will empower a new generation of today hardly realizable, or too costly to do so, applications and service; (ii) New sophisticated enterprise-wide monitoring and control approaches will be possible due to the prevalence of Cyber-Physical Systems (CPS); (iii) The different systems will be part of a larger ecosystem, where components can be dynamically added or removed and dynamic discovery enables the on-demand information combination and collaboration. All these are expected to empower the transformation to a digital, adaptive, networked and knowledge-based industry, as clearly stated by the Innovation Program Industry 4.0 (see Chapter 11 of [14] and the references therein, [15] and www.plattform-i40.de).

The emerging approach in industrial environments is to create system intelligence by a large population of intelligent, small, networked, embedded devices at a high level of granularity, as opposed to the traditional approach of focusing intelligence on a few large and monolithic applications. This increased granularity of intelligence distributed among loosely coupled intelligent physical objects facilitates the adaptability and re-configurability of the system, allowing it to meet business demands not foreseen at the time of design and providing real business benefits.

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